2007-09

Identifying roads and trails hidden under canopy using Lidar

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THESIS

IDENTIFYING ROADS AND TRAILS HIDDEN UNDER CANOPY USING LIDAR

by

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September 2007

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2007	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE Identifying Roads and Trails Under Canopy Using Lidar

5. FUNDING NUMBERS

6. AUTHOR(S) F. Espinoza, R. E. Owens

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

LIDAR data collected from four geographic regions are studied to determine the feasibility of reliably identifying roads and trails hidden under dense jungle and forest canopies. The four analyzed regions include the Elkhorn Slough in Central California (2005), Kahuku Training Area on the North side of Oahu Island in Hawaii (2005), La Selva Biological Station near Puerto Viejo de Sarapiqui, Costa Rica (1997), and Cougar Mountain Park in Bellevue, Washington (2001). Using the commercial product, Quick Terrain Modeler, 3-D interactive analysis was done to identify roads and trails hidden under canopy. Results are compared to overhead panchromatic imagery and verified by significant ground truth. Trails with widths of 2.5 meters and narrower were found with overall accuracies up to 85%.

14. SUBJECT TERMS Lidar, Ladar, Laser Radar, Foliage Penetration, FOPEN, poke-through, terrain analysis, trails, La Selva Biological Station, Elkhorn Slough, Kahuku, Cougar Mountain Park, IPB

15. NUMBER OF PAGES 128

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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IDENTIFYING ROADS AND TRAILS HIDDEN UNDER CANOPY USING LIDAR

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MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS

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ACKNOWLEDGMENTS

Special Thanks to:

Dr. R. C. Olsen, Naval Postgraduate School

Dr. Mark Abrams, Second Reader

CAPT Al Scott, Naval Postgraduate School

Daria Siciliano, Naval Postgraduate School

Angela Puetz, Naval Postgraduate School

Eric Van Dyke, Elkhorn Slough National Estuarine Research Reserve

Steven Sarigianis, U.S. Army-ERDC Topographic Engineering Center

Kim Hayes, Elkhorn Slough Foundation

Diana Martinez, Puget Sound Lidar Consortium

Ragde Sanchez, Organization for Tropical Studies

Raymond Irie, Kahuku Range Control

Mike Roth, Johns Hopkins University Applied Physics Lab

Andy Scheck, Johns Hopkins University Applied Physics Lab

Rich Stammler, National Geospatial-Intelligence Agency

Deirdre, Marissa and Esteban Espinoza

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I. INTRODUCTION

A. PURPOSE OF RESEARCH

There are a number of illicit organizations, such as narcotics traffickers, terrorists and insurgents operating in regions overgrown with dense forest or jungle canopy. 9.7% of terrestrial land is covered by the broadleaf evergreen biome as would be found in tropical rainforests and 7.9% is covered by evergreen needleleaf forests. (De Fries, R. S., Hansen, Townshend, J. R. G., & Sohlberg, 1998) The effectiveness of imaging systems to detect, track and locate operations in these dense canopy environments is severely limited. One possibility for "seeing through" dense canopies is to use inherent poke-through[1] capabilities of Lidar to provide georeferenced terrain classification; a capability that could aid in detecting, tracking and locating illicit operations previously undetectable. The purpose of this thesis is to determine if roads and trails[2] are identifiable under canopy using Lidar.

B. OBJECTIVE

The primary of objective of this thesis is to determine the capability, effectiveness and utility of using Lidar to accurately identify and classify roads and trails hidden under canopy. Roads and trails are identified by analyzing preexisting Lidar data collected from four distinct regions (near Monterey, California; Kahuku, Hawaii; Puerto Viejo, Costa Rica; and Bellevue, Washington). The collection dates ranged from 1997 to 2005 using varying sensors and collection techniques. Error matrices are created for three of the regions to calculate the accuracies of road and trail identification. The other region was utilized as a training site and is not included in the accuracy assessment.

[1] Use of the terms canopy poke-through and foliage penetration (FOPEN) are used interchangeably throughout this document and refer to the ability of Lidar pulses to pass between gaps in jungle or forest canopies and reach the understory and surface below.

[2] Through the remainder of this document, the term trails may be used to refer to roads, cart tracks and trails.

Additionally, a process will be created to guide Quick Terrain Modeler basic users through importing, manipulating, analyzing and exporting Lidar data for this purpose.

The following chapters will provide a brief background on Lidar, a detailed description and the results of the experiment. Chapter II will provide an introduction to Lidar and the post-processing software available for viewing and analyzing the data. Advantages Lidar offers over other systems for terrain analysis under canopy are discussed along with the reasoning behind choosing Lidar for this specific application. Military applications are identified along with a short description of the proposed theory. Chapter III will provide details of the experiment performed during this research along with detailed descriptions of the four regions, collection methods and systems used for each. A list of field equipment used throughout this research is also provided in Chapter III. Chapter IV breaks down the taxonomy adopted for classifying roads and trails and outlines the statistical methodology used to assess research accuracy. Finally, the observation and evaluation techniques used to identify roads and trails within the Lidar data are discussed along with a descriptions of artifacts commonly found in Lidar models. Chapter V includes the results of the experiment and provides interpretations for each region evaluated. Chapters VI and VII provide a summary of the research and the conclusions drawn from the research and experiment results.

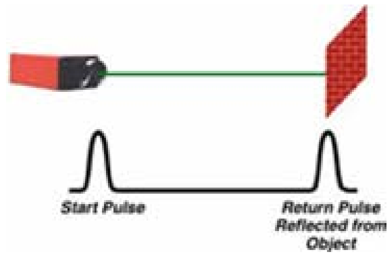
II. BACKGROUND

A. LIDAR

Lidar, for (Light Detection and Ranging), is an optical analogue to the more familiar RADAR systems. Lidar has been around "since shortly after the invention of the laser in 1958" and has been used for many different applications since its inception. (Ouellette, 2002) Technology advances in the last decade have made Lidar widely available in the commercial sector. Advances in laser technology, increased processing speeds, Inertial Measuring Unit (IMU) improvements and Global Positioning System (GPS) accuracy have dramatically increased the geolocation accuracy and point density. These advances directly enhance the canopy poke-through capabilities of Lidar systems. From lunar and planetary mapping to floodplain mapping, the processing power of today's personal computers (PCs) and the increased availability of commercial 3-D visualization software make Lidar accessible to a slew of varying disciplines.

Much like radar, Lidar emits a pulse of energy and detects the energy reflected off objects in the path of the emitted pulse. The main difference is that Lidar, unlike radar, uses a much narrower wavelength (near IR) providing greater spatial resolution than the wider wavelengths (RF) used by radar. Like radar, Lidar is an active sensor providing day or night capability, with the emitted energy invisible to the human eye.

To determine the range of an object from the sensor, the Lidar processor measures the difference between the time the pulse is emitted and the time the reflected pulse reaches the receiver (time of flight). The time of flight is multiplied by the speed of light and then halved to compensate for the two-way travel of the pulse. The result provides the range of the object from the sensor (Figure 1).



Object Range = (Speed of Light x Time of Flight) / 2

Figure 1. Lidar range calculation of reflected pulse (After: Optech)

To determine the object's geodetically referenced coordinates, the Lidar processing system combines the laser ranging, mirror scan angle, aircraft orientation (roll, pitch and yaw) and position. Aircraft orientation and position are provided by an onboard Inertial Navigation System (INS) and Global Positioning System (GPS) respectively (Figure 2).

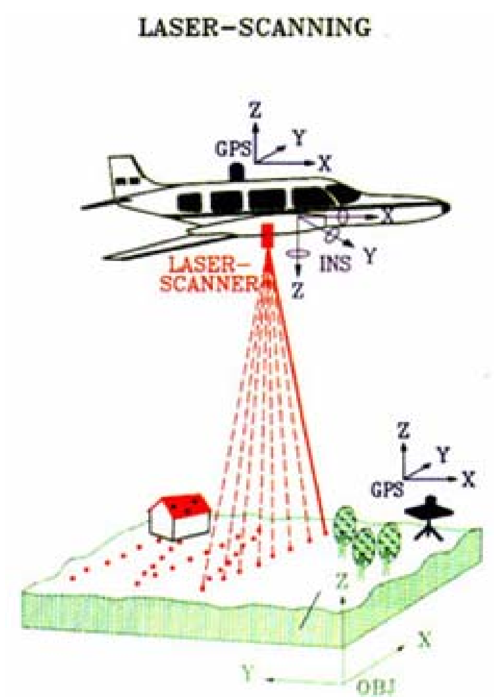


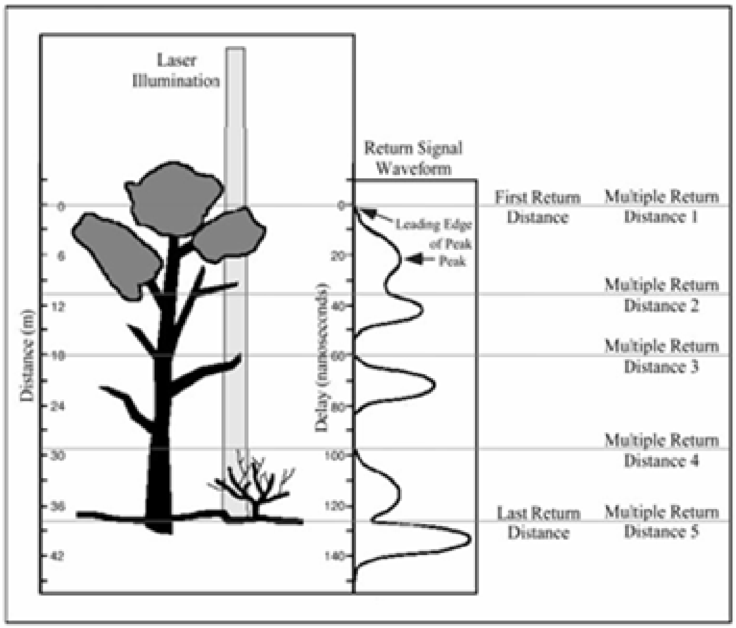
Figure 2. Lidar system integration (From: *Spencer B. gross, inc.*2007)

The pulse repetition frequency (PRF) indicates how many times per second the Lidar emits a pulse. “Firing the laser at thousands of pulses per second and scanning the beam across the terrain using a scan mirror generates a dense distribution of ranges to the surface” (Harding & Berghoff, 2000). Higher PRFs provide the following two benefits. Flown at the same altitude, a sensor with a higher PRF provides a higher point density than a sensor with a lower PRF, increasing the probability that more pulses will poke through the vegetation and reach the ground beneath. A higher ground point density equates to higher spatial resolution. The second advantage of higher PRF systems is that the sensor can be flown at higher altitudes and obtain the same resolution as a lower PRF system flown at a lower altitude. The advantage of flying a collection at higher altitudes is that the Lidar scanner ground swath will be wider, covering more area per collection pass.

Optech Airborne Laser Terrain Mapper (ALTM) systems were utilized for the collection of two data sets analyzed in this thesis. These ALTM systems operated at PRFs of 25 kHz (Elkhorn Slough) and 70 kHz (Kahuku). Another (Cougar Mountain) was collected with a Terrapoint ALTMS system operating at 30 kHz PRF. The fourth data set (La Selva) was collected with a FLI-MAP (for Fast Laser Imaging Mapping and Profiling) airborne laser mapping system which was designed, built and operated by John Chance Land Surveys, Inc. While little information is available regarding the sensor used, it is estimated that the system probably operated at approximately 8 kHz PRF based on the available technology in 1997. Today, John Chance Land Surveys, Inc. advertises FLI-MAP systems capable of operating at up to 250 kHz PRF.

Early versions of Lidar systems were only capable of recording a single return per pulse at low repetition rates. Today’s systems are capable of recording multiple returns per pulse at much higher PRFs. Single return systems were only capable of recording either the first (e.g. treetop) or last return (e.g. ground). Today’s multiple return systems are capable of capturing the first and last returns as well as a number of returns from points in between (e.g. tree branches). The most recent advancement is the digitization of the entire waveform, which “allows for many multiple returns with short separation to be

collected from a single laser shot." (Fowler, Samberg, Flood, & Greaves, 2007) Figure 3 illustrates "the conceptual differences between waveform recording and discrete return Lidar devices." (Lefsky et al., 2002)



"Illustration of the conceptual differences between waveform-recording and discrete-return Lidar devices. At the left is the intersection of the laser illumination area, or footprint, with a portion of a simplified tree crown. In the center of the figure is a hypothetical return signal (the Lidar waveform) that would be collected by a waveform-recording sensor over the same area. To the right of the waveform, the heights recorded by the three varieties of discrete-return Lidar sensors are indicated. First-return Lidar devices record only the position of the first object in the path of the laser illumination, whereas last-return Lidar devices record the height of the last object in the path of illumination and are especially useful for topographic mapping. Multiple-return Lidar, a recent advance, records the height of a small number (generally five or fewer) of objects in the path of the illumination."

Figure 3. Discrete-return and waveform-recording Lidar illustration (From: Lefsky et al., 2002)

Other technological advances include gimbaled sensors that enable the sensor to continue tracking along the intended flight line regardless of the aircraft's attitude. The ability to maintain track on the intended sensor flight line reduces gaps in data between each pass. This technique increases efficiency by reducing or eliminating the need to re-fly a collection swath due to gaps in data and by reducing the amount of overlap required for each collection pass. (Liadsky, 2007)

A step-stare technique developed and tested by JHU/APL is expected to further improve foliage penetration and long-range geolocation accuracy. The Innovative Lidar Applications Program (ILAP) system utilizes a gimbaled (two-axis, stabilized-pointing) Optech ALTM 3100D sensor to conduct a multi-look scan of an Area of Interest (AOI). As the system approaches the AOI, the gimbaled sensor is pitched in the direction of the AOI and commences scanning (adjusting the pitch of the sensor after each scan to maintain the AOI in view) (Figure 4). The scanning of the AOI continues until it falls outside the sensor's field of regard. (Roth et al., 2007), (Roth, 2007)

(a) (b) (c)

Figure 4. Step-Stare Mode: (a) first step, (b) second step (c) last step. (From: Roth et al., 2007)

In the step-stare mode, a 100 m x 100 m target area flown at 6000 feet above ground level can be scanned 22 times. The increased scans and scan angles provide a significant increase in point density per square meter, thus increasing the probability of increased surface point density. Figure 5 provides a visual comparison of data collected in single look (gimbals strapped-down) mode and a multi-look (step-stare) mode. The traditional strap-down pass collected 66k points whereas the step-stare pass collected 461k points; a point increase of almost seven times. (Roth et al., 2007)

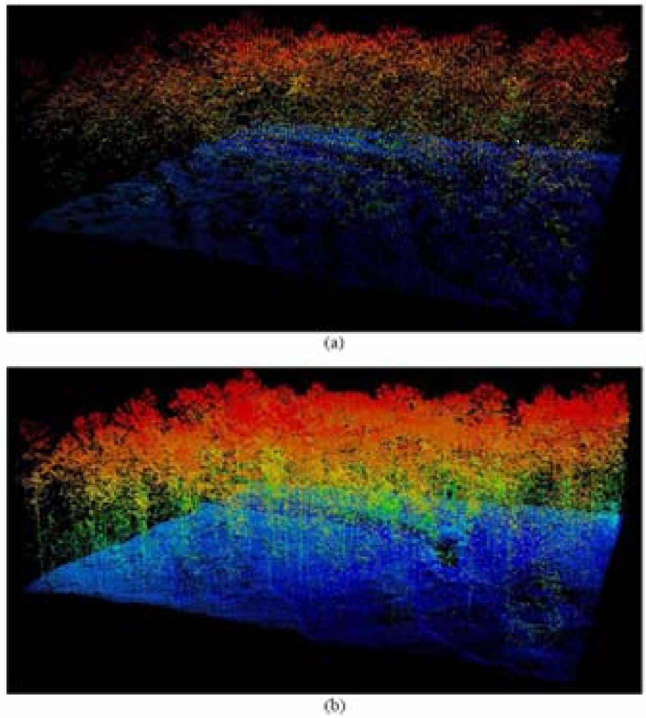


Figure 5. Model comparison of Lidar data collected in (a) Strap-down mode with 66K points and (b) step-stare mode with 461K points (From: Roth et al., 2007)

The collection of data sets analyzed in this thesis range from using decade-old to more recent technology and more advanced collection techniques. Advances in sensor technology, algorithms and collection techniques indicate that foliage penetration capabilities of Lidar will continue to increase.

B. POST-PROCESSING SOFTWARE

"Lidar processing software is one of the most exciting and rapidly evolving areas within the modern mapping disciplines." (Romano, 2007) As the popularity of Lidar continues to increase and new applications are identified, commercial software programs for viewing and working with the data have become more prominent. Previously, Lidar post-processing software was largely proprietary. Today, a number of software programs are commercially available for post-processing and viewing Lidar data.

Quick Terrain Modeler with a Bare Earth Extraction plug-in was used to analyze the Lidar data sets for this research (Figure 6). Quick Terrain Modeler is a 3-D modeling software package created to view and manipulate large amounts of complex data. The software was developed by JHU/APL and is now available for purchase commercially from Applied Imagery LLC. Most standard formats of Lidar data (LAS, ASCII XYZ, etc.) can be imported and used to build models supported by the software.

The Bare Earth Extraction Plug-in, developed by JHU/APL, "is a digital elevation model processing utility with functionality designed to facilitate the detection of man-made objects under canopy. The utility ingests XYZ points representing foliaged areas and sorts them into three distinct point files: one representing the estimated bare earth surface (the **surface** file), a second representing foliage (the **cloud** file), and a third (the **object** file) that includes points classified as non-surface but whose height above the estimated ground level (AGL) falls below a user-specified limit." (JHU/APL, 2006)

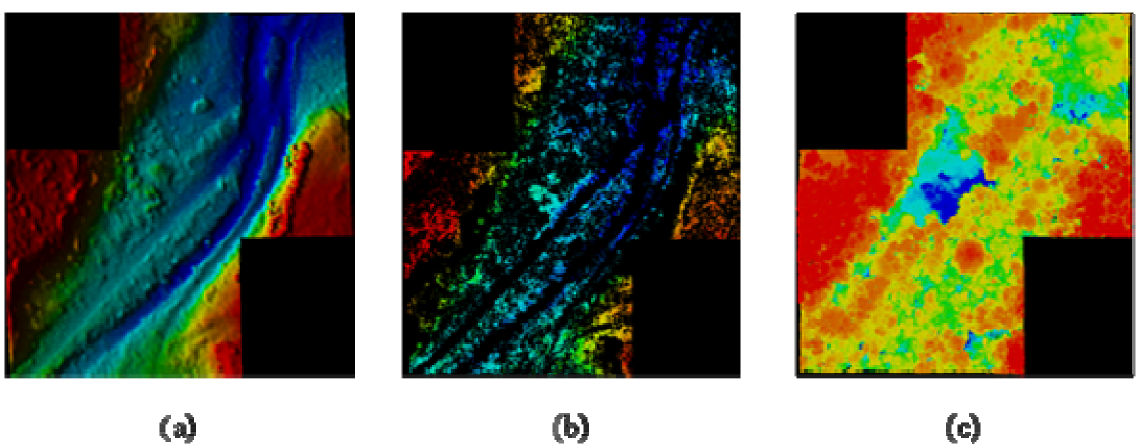


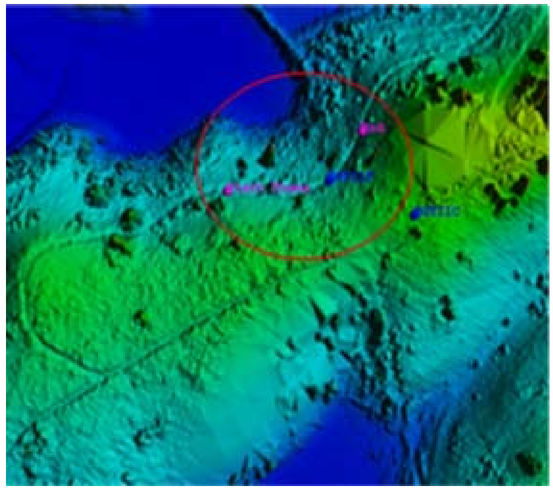
Figure 6. Examples of Bare Earth Lidar Models: (a) Surface, (b) Object, (c) All Points (Cloud)

C. ADVANTAGES OF LIDAR

"Lidar systems have become the sensor of choice for mapping vegetated regions when elevation measurements beneath canopy are needed." (Hensley, Munjy, & Rosen,

2007) Unlike photogrammetry systems requiring ambient illumination, Lidar is an active sensor capable of operating day or night. This gives it the ability to collect terrain data in heavily shadowed areas (Figure 7).

(a)



(b)

Figure 7. Elkhorn Slough comparison of (a) shadowed overhead imagery (From: Google Earth) and (b) Lidar image of same area.

In addition to areas obscured by shadows, Lidar's ability to provide surface data under canopy gives it another distinct advantage over other remote sensing technologies. As described in section A of this chapter, vegetation poke-through is enhanced by the extremely high PRF rates of current systems combined with the ability to acquire multiple returns per pulse. Additionally, the narrow light pulses (NIR) associated with Lidar create a small footprint able to poke through and collect surface data through gaps in the canopy. This narrow footprint offers a distinct advantage over broader radio waves in ordinary radar systems for surface modeling under canopy. With regards to Photogrammetric imaging, "leaf-off" conditions are generally required to allow surface data collection through vegetation, greatly limiting when surface data under canopy can be collected. In regions where there is no leaf-off season such as tropical regions and coniferous forests, Photogrammetric systems provide little or no utility in providing surface characteristics under canopy. (Molander, Merritt, & Corrubia, 2002)

Some Lidar systems are currently capable of producing Digital Terrain Models (DTMs) to elevation accuracies of better than +/- 15 cm (6 in). High accuracies, along with a high ground point density (up to 40 points per square meter), create highly accurate DTMs. Additionally, Lidar can produce DTMs faster and often more economically than similar products produced using any other technology. (Spatial Resources, 2007)

Lidar data is inherently georeferenced, which means it can directly interface with Geographic Information Systems (GIS) applications, and makes it easily applied to mapping. (*Spencer B. gross, inc.*2007) Lidar systems are not usually affected by reflectivity of objects. It is possible for highly reflective objects to saturate some detectors and other objects may have returns too weak to register. In addition, Lidar can measure targets from any angle, is not affected by background noise, and is unaffected by temperature variations. (Optech)

One challenge is the high density of points captured by Lidar systems, which directly results in extremely large file sizes. In many cases, it is necessary to partition Lidar data into smaller files for managing and viewing the data. Table 1 gives a general idea of the file sizes necessary to accommodate Lidar data sets:

Area	1-meter Resolution	2-meter Resolution	3-meter Resolution	4-meter Resolution	5-meter Resolution
1 square mile	77 MB	19 MB	8.5 MB	5 MB	3 MB
1 square kilometer	30 MB	7.5 MB	3 MB	2 MB	1 MB

Table 1. Approximate file sizes for raw *x, y, z* point data in ASCII format. (From: NOAA, 2006)

D. WHY LIDAR?

Remote sensing is the most desirable method to identify roads and trails in areas that cannot be readily accessed. Many of the proposed applications for this research involve roads and trails to be identified in “unfriendly” areas where it is not safe or practical to survey from the ground. In many cases, the vegetation canopies will not

allow for imaging systems alone to provide the necessary information to create a useful terrain model. The Lidar characteristics mentioned in the previous section make it a logical candidate for such applications.

Lidar data is currently used by many agencies to produce what are commonly referred to as DTMs or Digital Elevation Models (DEMs). While there are various accepted definitions for these terms, for the purposes of this thesis, a DTM and DEM are synonymous and represent the "bare earth terrain with uniformly spaced z-values." (Maune, Kopp, Crawford, & Zervas, 2007) A study performed by Hodgson et al. (July 2002) compared the elevation accuracy of Lidar-derived models, IFSAR (interferometric synthetic aperture radar)-derived models, and U.S. Geological Survey (USGS) Level 1 and 2 DEMs under leaf-on conditions. The results of the comparison found airborne Lidar provided better elevation accuracies than the other methods under these conditions. (Hodgson, Jensen, Schmidt, Schill, & Davis, 2003)

In the Hodgson study, additional elevation error was introduced with differing terrain slopes and vegetation (short and tall grass, pine tree canopy, scrubs/shrubs). Most of the elevation error due to slope is believed to be a direct result of horizontal error (Figure 8). Although accurate assessment of actual elevation is important, for identifying roads and trails, the primary concern is relative elevation (i.e., elevation of one point relative to a point in a nearby area) necessary to identify key features such as linear depressions.

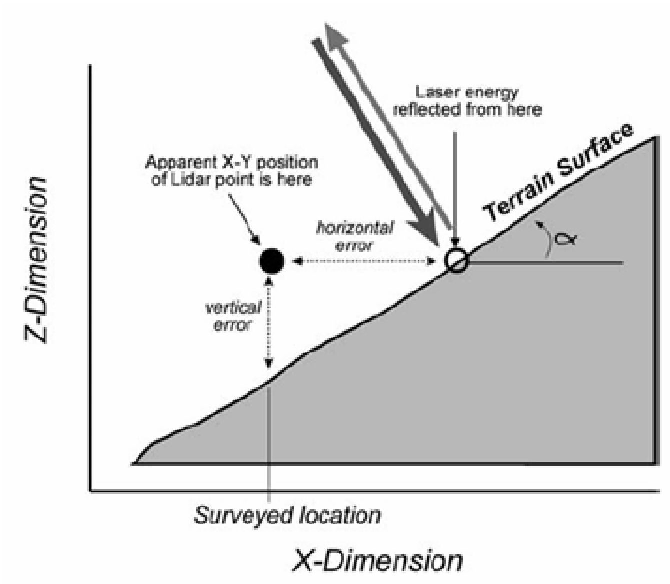


Figure 8. Illustration of observed elevation error caused by terrain slope and horizontal error. (From: Hodgson & Bresnahan, 2004)

Elevation error caused by vegetation greatly affects the ability to identify roads and trails. This type of error suggests that certain types of vegetative land cover categories intercept so many of the Lidar pulses that the distribution of surface points is too sparse to provide an accurate model. Multi-story vegetation poses a significant problem for creating accurate DEMs as it can "confuse" the automated bare earth algorithms, as they may not be able to assess the last returns as ground points accurately. (Hodgson et al., 2003) Future Lidar systems are expected to be able to produce better DEMs by allowing more points to reach the surface. "Much higher ground resolution can be achieved by integrating multiple looks from several look-angles." (Roth et al., 2007) The step-stare technique described in Section A of this chapter should provide greater point density while scanning multiple angles, therefore increasing the likelihood of finding gaps in the canopy. Ultimately, this increased surface point density should provide high resolution DEMs that facilitate the identification of roads and trails under canopy.

E. MILITARY APPLICATIONS

When executing military operations it is necessary to understand the battlefield and the options it presents to both friendly and enemy forces. (United States. Dept. of the Army, 1994) Terrain Analysis, a subset of Intelligence Preparation of the Battlespace (IPB), is a key element in maneuver warfare. Traditional methods of terrain analysis, such as the use of maps, overhead imagery, reconnaissance and other remote sensing applications do not provide the georeferenced resolution that Lidar can provide in remote, densely vegetated areas. While Lidar will not supplant traditional methods, it can enhance battlespace preparation by providing an ability to remove layers of vegetation to expose many different terrain features and objects previously obstructed using other sensors.

With regards to roads and trails, terrain analysis seeks to identify mobility corridors, avenues of approach and their related choke points. In addition to identifying mobility corridors, an important function that Lidar can provide is estimates of road or trail width, turn radius and slope. This enables operational planners to determine the type of armament that can be maneuvered in the battlespace.

In heavily vegetated areas, roads and trails under canopy are traditionally mapped through ground reconnaissance. Lidar will not supersede the need for reconnaissance forces, but can be used to identify previously unknown roads or trails enabling operational planners to more quickly prepare the battlespace and focus reconnaissance forces more efficiently. When facing small footprint forces such as insurgents, the ability to identify roads or trails under canopy may be the human activity indicator that points to where those forces assemble or deploy. Once the roads and/or trails are identified in post flight processing, other post-processing techniques can be applied to that same data to identify additional man-made objects hidden beneath the canopy (e.g. vehicles, buildings, encampments, etc.). In other words, the roads or trails will be the arrow that points to the proverbial needle in the haystack. Although not under tree cover, tank tracks visible in the Lidar image below provides a clear example of how roads, trails or even tracks could lead to man-made objects of interest (Figure 9). In addition to exposing many terrain

features under canopy, accurate coordinate information derived from Lidar models, can be used to conduct operations at both the tactical and operational levels.

(a) (b)

Figure 9. (a) Visible-light photograph of tank under canopy, (b) Lidar image of tank with camouflage net gated out (From: Gschwendtner & Keicher, 2000)

Day or night capability and the small equipment footprint of Lidar make it an ideal candidate for Unmanned Aerial Vehicle (UAV) integration. Extended on-station times provided by UAV systems would increase the dwell time required for significant canopy poke-through of large geographic areas. Equipping the UAV with a data downlink could provide near real-time processing capability. This approach would also mitigate the risk inherent to manned flight over hostile areas. (Office of the Secretary of Defense, 2005) To this end, in 2005 a research and development contract was awarded to Harris Corporation to develop and demonstrate the JIGSAW Lidar 3-D imaging system for use on a DP-5X Helicopter UAV. ($6.6M for UAV-mountable LADAR.2005) A sensor specifically designed by Lincoln Laboratory scaled to fit the DP-5X Helicopter was tested at the Army Redstone Technical Test Center in Huntsville, Alabama. The test was conducted with the sensor mounted on a UH-1 helicopter. It demonstrated the ability of the small footprint sensor to identify objects under canopy. (Marino & Davis, William R., Jr., 2005)

F. THEORY

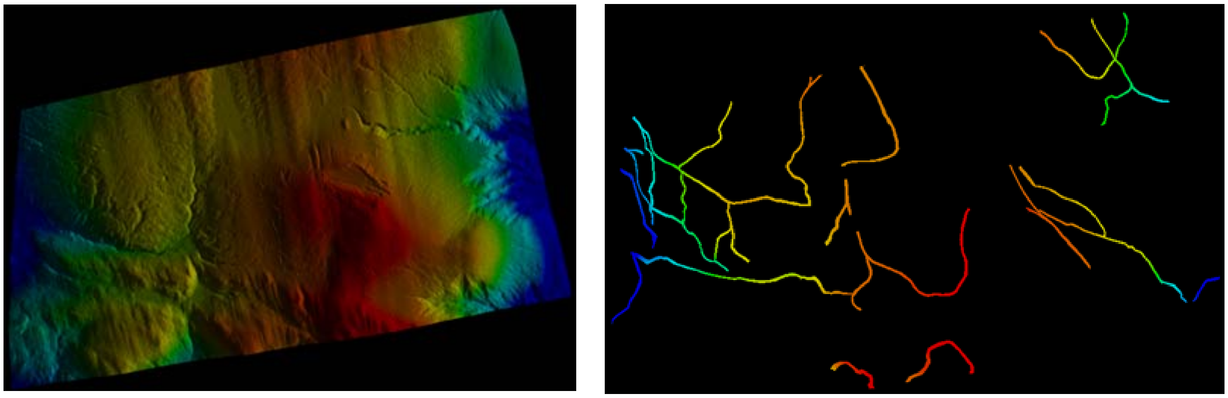
The theory of this thesis is that roads and trails hidden under canopy can be identified using Lidar. The advances in Lidar sensor technology, collection techniques, processing power, and post-processing software indicate that Lidar foliage penetration capabilities will continue to increase over time. Data sets analyzed in this thesis vary in sensor technology, collection techniques, collection platforms, and terrain/vegetation makeup; additionally, data collection dates range from 1997 to 2005. The results obtained through this analysis will attempt to verify the postulated theory and provide an indication of increased foliage penetration capabilities achievable with advances in Lidar technology.

III. EXPERIMENT DESIGN

A. OVERVIEW

Four preexisting data sets from various locations were used throughout the course of this research. It should be noted that none of the data sets were collected specifically for the purpose of finding roads and trails. The Elkhorn Slough data set was utilized exclusively as a training site to familiarize the researchers with Lidar data formatting, determine initial feasibility of locating roads and trails and learn the idiosyncrasies of manipulating Lidar data using the post-processing software. After becoming familiar with the software, data sets and GPS equipment as well as making an initial feasibility decision, an experimental plan was formulated for quantifying the ability to identify roads and trails using Lidar data. While some steps varied due to differences in data sets and lessons learned during each subsequent site visit, the basic principles were maintained for each location. The process was performed in its entirety for each site (excluding the training site) before moving on to the next data set.

The initial step for each site was to apply the bare earth algorithm to the data set. After the bare earth algorithm was applied, the surface and object files were analyzed by following a process created for identifying, locating and classifying potential roads and trails (see Appendices D and E). After identifying possible roads and trails, the data sets were cropped, leaving only the identified roads, trails and minimal area on each side (Figure 10). These models were saved separately, exported as ASCII XYZ files and identified as “target” areas. Approximate areas of the target areas were measured with the Quick Terrain Modeler area statistics tool. For “control” areas, a portion of the original model with no trails identified and having approximately the same area as the target area was then cropped out.



(a) (b)

Figure 10. (a) Cougar Mountain Test Area and (b) corresponding Cropped Target Areas.

Based on the total area of the cropped models, a determination was made as to how many "target points" and "control points" would be required to conduct field validation. This process is explained further in Chapter IV. To provide randomization, the target and control ASCII XYZ files were placed into IDL with locally produced code designed to randomly generate a specified number of points for each target and control set. Each randomly generated point was labeled with a unique "target" or "control" number for identification purposes. The names and coordinates for all target and control points were then imported into the Garmin MapSource program and transferred to the handheld GPS units for ground truth verification.

During each site visit, ground truth verification was attempted for each target and control point. For the Kahuku site visit, if a target or control point fell within five meters of another, only one point was counted for the statistical analysis and the others were discarded. For subsequent sites visited, additional IDL code was written to prevent generating target or control points falling within a specified distance from another point (5 meters for La Selva and 10 meters for Cougar Mountain).

Verification consisted of searching a seven-meter radius around each target and control point to determine if any portion of a trail fell within that area. If a point fell on a trail or within seven meters of a trail, the point was classified as "trail" for statistical

purposes. Conversely, if no trail was found within seven meters of a target or control point, the point was classified as “no trail.” The seven-meter buffer was included to allow for cropping errors, rounding of UTM coordinates, and GPS positioning errors. In addition to classifying each point as “trail” or “no trail,” other information was collected for all target and control points falling on or near trails. This data was used to assist in determining physical characteristics that may help or hinder accurate point classification through viewing of Lidar data.

At each site, GPS track logs were kept for comparing GPS elevations to the elevations provided by the surface models created using Lidar data. This was accomplished by first saving the GPS track logs as text files. These files were then opened in Microsoft Excel and reduced to the x, y, and z UTM coordinates. The x and y values of these coordinates were imported into the Quick Terrain Modeler program as “markers” and the elevation (z-value) was interpolated to place the marker on the surface model at ground level. A spreadsheet was then created to provide a point-by-point comparison of the GPS recorded elevations and the Lidar surface model elevations. A couple of differences between the two types of elevation values should be noted. First, the GPS elevations are measured to the nearest whole meter while the Lidar models provide elevation measurements in meters carried out six decimal places. This can cause the GPS recorded elevation changes to appear more extreme (minimum changes of one meter) in the comparison graphs, while the Lidar elevation values change more gradually. Second, the GPS measurements are from an antenna carried in a backpack approximately two meters off the ground. No adjustments were made to the GPS recorded elevations to account for this distance.

B. DATA SET LOCATIONS

Lidar data of four distinct geographic regions with differing biomes were analyzed in this thesis. Sites include Elkhorn Slough and surrounding Elkhorn Highlands, located on the central coast of California (Figure 11); Kahuku Training Area, on the North side of Oahu, Hawaii (Figure 12); La Selva Biological Station, near Puerto Viejo de Sarapiqui in Costa Rica (Figure 13); and Cougar Mountain Regional Wildland

Park, located between the cities of Bellevue, Newcastle and Issaquah, Washington (Figure 14). A detailed description of each site and corresponding data sets is provided in Chapter III.

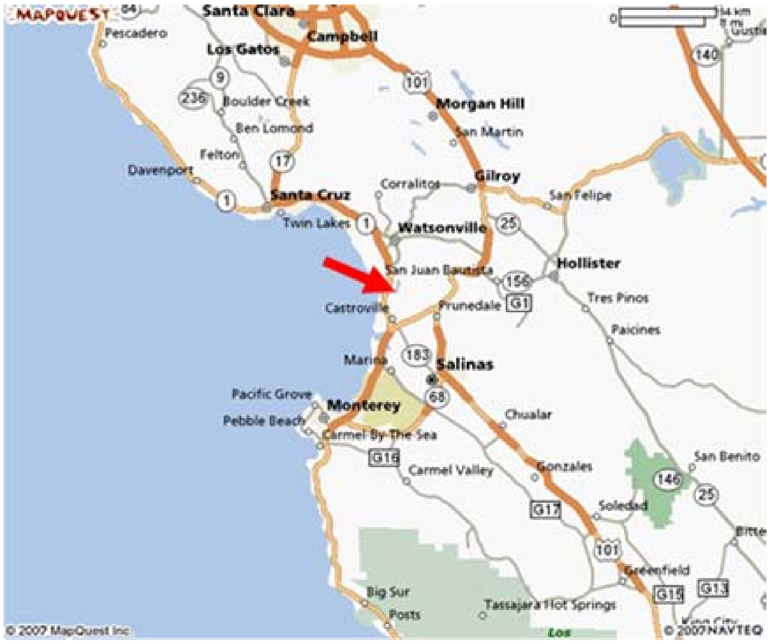


Figure 11. Elkhorn Slough, California.(From: MapQuest)

Figure 12. Kahuku Training Area, Hawaii.(From: MapQuest)

Figure 13. La Selva Biological Station, Costa Rica (From: MapQuest)

Figure 14. Cougar Mountain Park, Washington (From: MapQuest)

C. SITE DESCRIPTION AND COLLECTION METHODS

In the site descriptions that follow, close attention is paid to describing typical road and trail composition to include topography features such as slope as well as canopy and undergrowth composition. Metadata presented will differ from site to site due to the availability of information at the time of writing. Appendix F contains additional pictures to provide examples of typical trails and canopy cover found at each of these sites.

1. Elkhorn Slough

Elkhorn Slough is part of a National Estuarine Reserve located in central Monterey Bay, California and winds inland seven miles. "To the east of Elkhorn Slough is a series of ridges covered with the rare maritime chaparral plant community." (Elkhorn Slough Foundation and Tom Scharffenberger Land Planning and Design, 2002) Three training sites were chosen based on trail type, canopy cover, vegetation density, trail slope and accessibility. Site visits were performed in March, 2007. Site 1 (Elkhorn Slough Five Fingers Loop Trail) contained a Eucalyptus tree stand with sparse undergrowth (Figure 15a). The topography was relatively flat with a four-meter wide mowed grass trail. Site 2 (Manzanita Park) contained a mixed tree stand (Eucalyptus, Coast Live Oak and Conifer) with varying understory density (Manzanita and other chaparral associated shrubs) (Figure 15b). The trails varied in width from one to two meters with a pronounced slope on the eastern side of the area. Site 3 (Long Valley Canyon Road) contained primarily Coast Live Oak tree stands; with varying understory density (Chaparral associated shrubs) (Figure 15c). (Elkhorn Slough Foundation and Tom Scharffenberger Land Planning and Design, 2002) The primary trail (three meters wide) followed the valley floor with smaller trails (two meters wide) branching off in both directions. All trails appeared to follow natural drainage routes. The elevation difference between the highest and lowest trail points was approximately 90 meters. Although Long Valley Canyon Road is locally mapped, this area is protected land with restricted access. Nevertheless, there remains an established road and trail network. These training sites were used to establish a strategy to assess the ability to identify trails under canopy at the remaining sites (Kahuku, La Selva and Cougar Mountain Park) statistically.

(a) (b) (c)

Figure 15. Elkhorn Slough (a) Five Fingers Loop Trail (b) Manzanita Park (c) Long Valley Canyon Road (From: Google Earth)

Airborne 1 utilized the Optech ALTM (Airborne Laser Terrain Mapper) 2025 to conduct the Elkhorn Slough survey in April, 2005 (Table 2). (Airborne1, 2005) Figure 16 depicts the flight lines mapped by Airborne 1. IKONOS visible imagery (October 23, 2000) was utilized to select the candidate areas of interest.

Airborne 1 Lidar Collection Parameters	
Collection Date	12 April 2005
Collection Rate	25,000 pulses/second
Wavelength	1064 nm (NIR)
Altitude	1828 m
Strip Width	+/- 18 deg. 1200m GSD
Pulse Return Classification	1. Extracted Feature – Last Pulse
	2. Bare Earth – Last Pulse
	3. Extracted Feature – First Pulse
	4. Bare Earth – First Pulse
Point Spacing	1 m posting gridded to 2.4m
Platform	Airborne 1(fixed-wing twin prop)
Datums	UTM Zone 10, NAD83, NAVD88 meters

Table 2. Elkhorn Slough Collection Parameters (From: Airborne1, 2005)

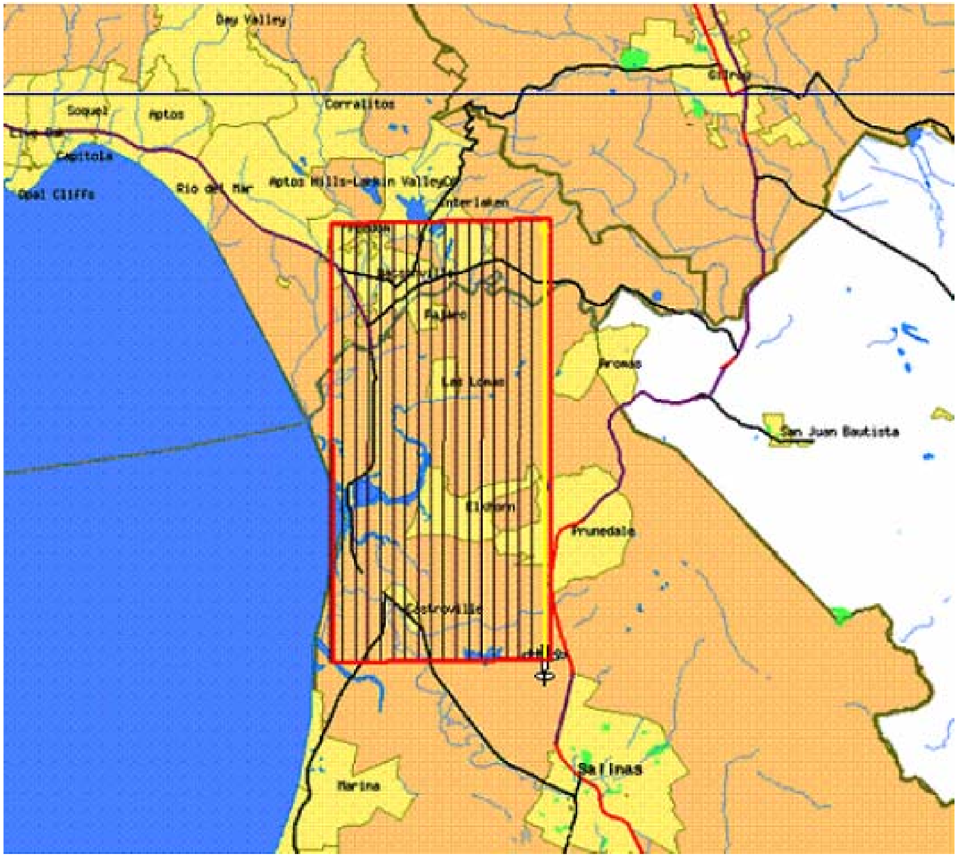


Figure 16. Airborne 1 Flight Profile for Elkhorn Slough Collection. (From: Airborne1, 2005)

2. Kahuku

The Kahuku Training Area, situated on the north side of Oahu, Hawaii is primarily comprised of lowland mesic grasslands and forests. (Whelan, 2007) Its rugged mountainous terrain and varying degree of vegetation make it well suited for mountain and jungle warfare training of company-sized units (65-200 soldiers) and smaller. (PACOM) This location ideally simulates roads and trails that would be utilized by insurgent, narcotics trafficking or terrorist organizations operating in a jungle environment.

Lidar data analyzed for the Kahuku Training Area was obtained courtesy of the National Geospatial-Intelligence Agency (NGA). The data was collected using a

modified Optech 3100D onboard a Bell 206 Jet Ranger helicopter in March, 2005. A ground truth site visit was performed in May, 2007. Flown to simulate the step-stare mode described in Chapter II, seven sites "chosen to represent different levels of vegetation" were used for this data set analysis (Figure 17). (Stammler et al.) With the exception of Site 6 (a-c) that has an approximate total area of 400 m x 400 m, all Kahuku sites have an approximate area of 100 m x 100 m. Of the seven sites evaluated prior to the visit, only Sites 1 - 6 were accessible during the ground truth site visit. Prior site knowledge was limited to the fact that a maintenance road traversed all seven sites. However, no georeference information was used to assist in identifying and classifying the road when analyzing the Lidar data.

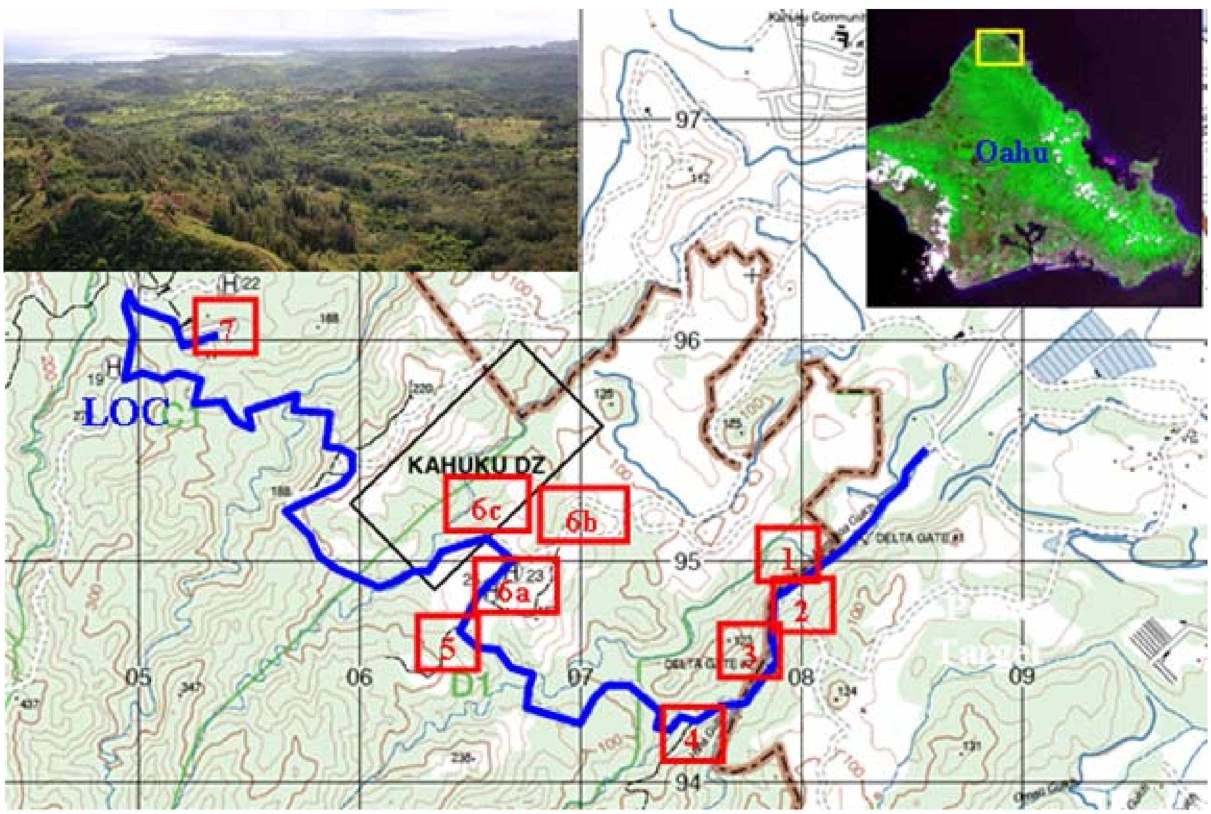
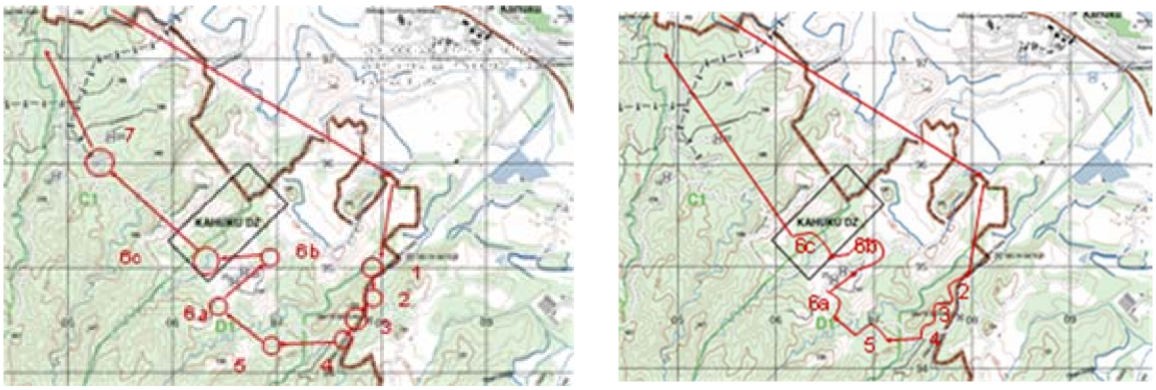


Figure 17. Kahuku Training Area Sites (From: Stammler et al.)

To simulate the step-stare mode, several collection passes were conducted using various look angles. Look angles varying from nadir to 45 degrees off nadir were achieved by adjusting altitude and offset while staring at the AOI (site). The nadir

collection, flown at an "altitude necessary to achieve" a ground resolution of one foot, was flown with a 360-degree flight profile around each site (Figure 18a). Flight profiles for look angles of 15, 30 and 45 degrees achieved collection profiles greater than 90 degrees but less than 180 degrees as they flew by each site (Figure 18b). (Stammler et al.)



(a) (b)

Figure 18. Flight profile examples (a) Nadir collection 360-degree flight profile (b) 30-degree look angle flight profile (From: Stammler et al.)

As stated earlier, the Optech 3100 was outfitted with custom modifications, one being the Full Wave Digitizer (FWD). "In a traditional Optech ALTM system only the first, last return and most intense return are saved." The FWD on the other hand "captures and retains the full waveform permitting small under-vegetation signals to be processed," thereby providing a clearer definition of the forest or jungle understory. (Stammler et al.) An abbreviated specification table of the Optech 3100D sensor is found in Table 3.

Sensor	Optech ALTM 3100
Collection Date	March 2005
Collection Rate	70,000 pulses/second
Wavelength	1064 nm (NIR)
Altitude	2,000 ft and 6,562 Ft
Spot Distribution	Sawtooth
Pulse Return Classification	Intelligent Waveform Digitizer
	8 bits @ 1nsec sample interval per pulse
	(max 50 kHz)
Ground Spatial Resolution	1ft (@ 2,000 ft. Altitude) 1 m (@ 6,562 ft. Altitude)
Platform	Bell 206 Jet Ranger Helicopter

Table 3. Optech 3100 Specifications (From: Stammler et al.)

3. La Selva Biological Station

"At the confluence of two major rivers in the Caribbean lowlands of northern Costa Rica, La Selva comprises 1,600 hectares (3,900 acres) of tropical wet forests and disturbed lands. It averages 4 meters (over 13 feet!) of rainfall that is spread rather evenly throughout the year. Located within the tropical and premontane wet forest, the Station has about 73% of its area under primary tropical rain forest." (*Organization for tropical studies.*) "The forest is structurally complex, consisting of upper canopy layers 44 to 55 meters high, small suppressed trees from 10 to 25 meters high, and dense, low-level ground cover. The canopy closure is generally high, about 98 – 99 percent, which is a common closure for broadleaf evergreen forests." (Hofton, Rocchio, Blair, & Dubayah, 2002) Although maps of the La Selva trail network exist, they were not viewed prior to or during the analysis of the Lidar models (see La Selva map in Appendix A).

The La Selva data was collected in 1997. A ground truth site visit was conducted in June, 2007. The large time lapse between the collection date and site visit posed some challenges that will be discussed in further detail in Chapters V and VI. Collection parameters and sensor specifications were unavailable at the time of writing.

4. Cougar Mountain Regional Wildland Park

Cougar Mountain Park "covers more than 3,000 acres and is the largest park in the 20,000-acre King County Park System…Cougar Mountain Park is famous for its many trails - more than 36 miles of trails for hiking, and over 12 miles for equestrians." (*King county parks.*2007) The park has a diverse history:

- Coal was mined from the area for nearly a century beginning in 1864.
- Anti-aircraft guns were installed to protect Seattle during World War II.
- The site served as a NIKE Missile air defense facility from 1957-1964.

"Lush with vegetation, the old-growth forest was cut for support beams in the mines, so second growth predominates. Red alder, big leaf maple, Sitka spruce, western red cedar, Douglas fir and western hemlock mingle with a variety of shrubs and ferns." (Sykes, 2000)

The Cougar Mountain Park test area (Figure 19) was selected for its size (3.5 km x 2 km), dense canopy cover and accessibility; as identified by viewing Google Earth. With the knowledge of the existence of an extensive trail network, the road (Clay Pit Road) and large clay pit area clearly visible in both overhead imagery and Lidar data offered little additional value to the research. For this reason, a decision was made to remove these areas from the target area prior to target point generation. Lidar data for this test area was provided courtesy of the Puget Sound Lidar Consortium (PSLC). An extensive library is publicly available and can be requested through their website at http://pugetsoundlidar.ess.washington.edu . Figure 20 indicates the amount of Lidar data available through the PSLC and how it is divided into grids. Figure 20b identifies the area including and surrounding the Cougar Mountain area evaluated.

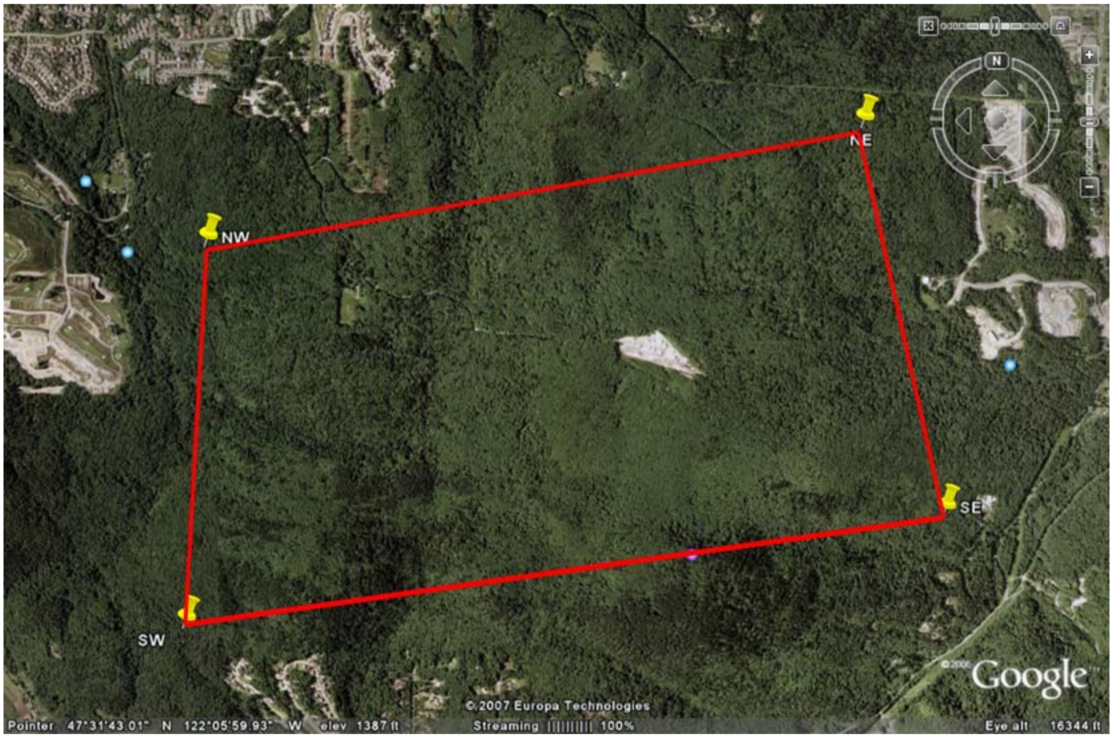
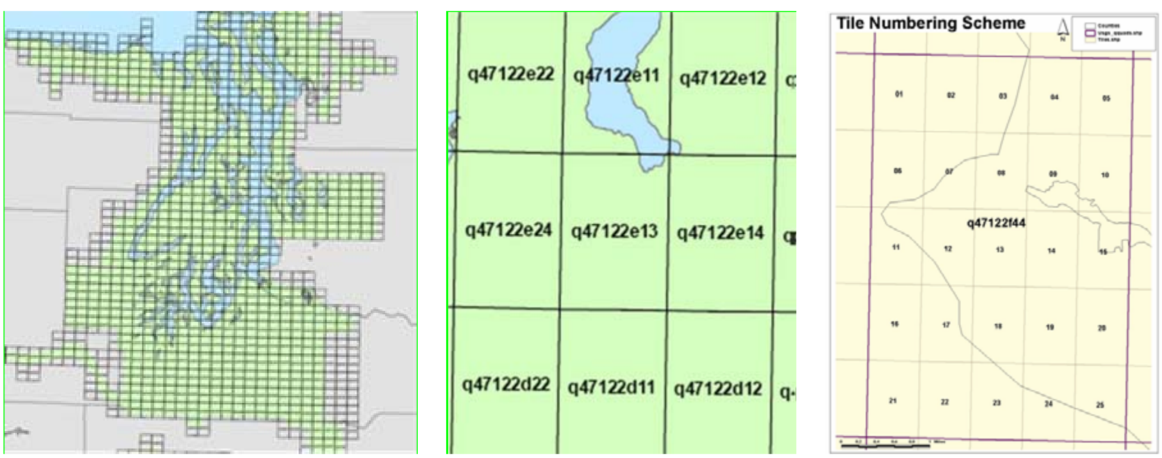


Figure 19. Cougar Mountain Park test area (From: Google Earth)



(a) (b) (c)

Figure 20. PSLC Lidar Data: (a) PSLC Index Map (b) PSLC Index Map zoomed in on area containing Cougar Mountain Park (c) Example of Puget Sound numbering scheme within each grid of Index Map (From: PSLC, 2005)

"Lidar data were collected in leaf-off conditions (approximately November, 2000 – April, 2001) from a fixed wing aircraft flying at a nominal height of 1,000 meters above ground surface. Flying height and airspeed were chosen to result in on-ground pulse spacing of about 1.5 meters in the along-swath and across-swath directions. Most areas were covered by two swaths, resulting in a nominal pulse density of about one pulse per square meter…they (ground returns) are regularly gridded at a 6-foot post-spacing and were derived using TIN (Triangulated Irregular Network) processing of the ground point returns." PSLC estimates vertical accuracy in flat areas to be 30 cm or less. (PSLC, 2005) More detailed information can be obtained from the PSLC website. A ground truth site visit of Cougar Mountain Park was accomplished in August, 2007.

Cougar Mountain Park Collection Parameters	
Sensor	Terrapoint ALTMS
Collection Date	January, 2001 (Leaf-Off Conditions)
Collection Rate (PRF)	30,000 pulses/second
Wavelength	1064 nm (NIR)
Altitude	1,000 m
Vertical Accuracy	30cm or less in flat areas
Pulse Return Classification	4 returns / pulse
Point Spacing	1.5 m posting gridded to 6-foot post- spacing
Platform	Fixed-wing twin prop

Table 4. Cougar Mountain Park Collection Parameters (After: PSLC, 2005)

D. FIELD EQUIPMENT

Table 5 identifies equipment utilized during ground truth verification site visits:

FIELD EQUIPMENT	
Equipment	**Description**
Garmin GPSMAP 60CSX	Hand-held GPS receiver used to verify target and control points
Antcom L1 TNC female 5" ground plane, 5/8" mount, 35db	GPS External Antenna (Backpack Mounted) for increased GPS accuracy and signal acquisition under canopy.
Leica DISTO A6	Handheld Laser Range Finder to measure trail widths
Bushnell Elite Model 1500	Laser Range Finder used to determine tree height
SONY Cyber-shot, DSC-V1 (5.0 mega pixels)	Digital camera used to capture overhead cover and trail characteristics
Western Digital Passport External Hard Drives with 120 GB of Memory	Transporting data sets and other critical information while executing ground truth operations during site visits

Table 5. Field Equipment

IV. OBSERVATIONS

A. CLASSIFICATION METHODOLOGY

To establish classification standards and a collection methodology, existing trail classification standards were identified that would provide a desirable taxonomy. The Army uses a route-classification formula to determine what vehicle and traffic load a specific portion of a route can handle. The route-classification formula consists of the following route features (United States. Dept. of the Army, 1998):

- Route width, in meters.
- Route type (based on ability to withstand weather).
- Lowest military load classification (MLC).
- Lowest overhead clearance, in meters.
- Obstructions to traffic flow (OB), if applicable.
- Special conditions, such as snow blockage (T) or flooding (W).

Due to the time restrictions of this study, width was the only characteristic used to classify roads and trails. Five classes were adopted based on lane widths currently shown on US military maps, Table 6. This classification scheme will help differentiate and quantify the ability to identify roads and trails of different sizes.

Class	Meters	Feet
Trail	Less than 1.5	Less than 5
Cart Track[3]	At least 1.5 but less than 2.5	At least 5 but less than 8
One Lane Road	At least 2.5 but less than 5.5	At least 8 but less than 18
Two Lanes Road	At least 5.5 but less than 8.2	At least 18 but less than 28
More than two lanes	At least 8.2	At least 28

Table 6. Lane Widths Currently shown on US Military Maps (After: United States. Dept. of the Army., 1992)

Figure 21 provides a visual representation of the terms used to describe recorded measurements. The first measurement was the width of the traveled way. The traveled way is that portion of the depression that either by design or through heavy traffic is available for vehicular or foot traffic. A second measurement, taken to capture the extreme width, included the width of the shoulders and the traveled way. In the case of unpaved roads, cart tracks or trails, the extreme width was measured from one side of the depression to the opposite side. In cases where a depression is created by berms on either side of the traveled way, the extreme width was measured from the top of one berm to the other. There are many more variations of how to measure the extreme width. Because there are so many variations, these measurements were not used to perform any statistical analysis. Nevertheless, it is important to note that the extreme width, not the traveled way, will usually provide the visible depression to queue the analyst. Figure 22 illustrates the measurements taken to classify each point.

[3] "Cart Tracks are natural traveled ways including caravan routes and winter roads. They are not wide enough to accommodate 4-wheel military vehicles…irregular turns and bends; traveled roadway width varies; apparent lack of direction; roadway detours around wet terrain." (United States. Dept. of the Army., 1992)

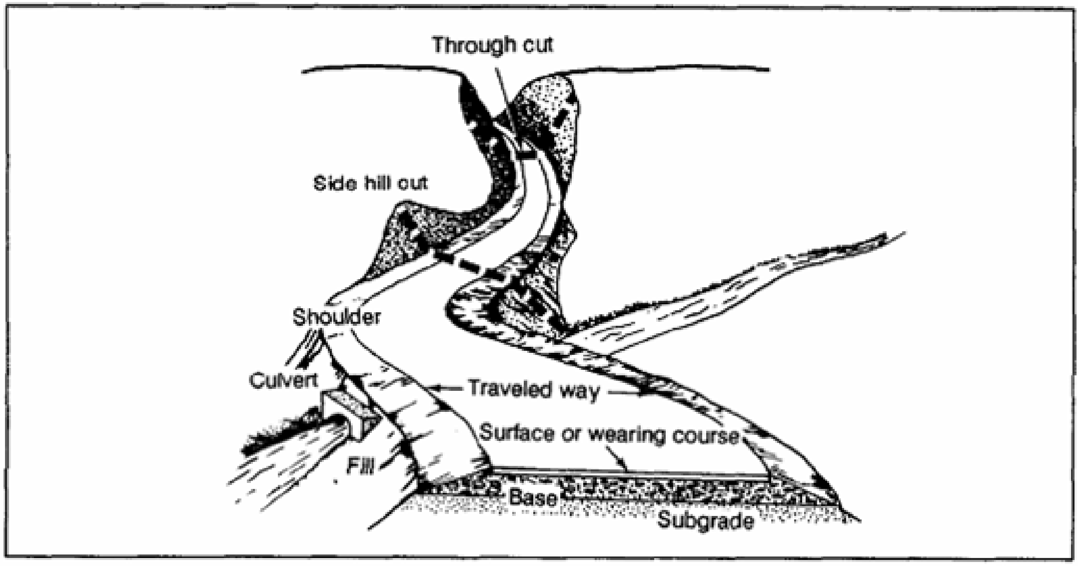


Figure 21. Parts of Road (From: United States. Dept. of the Army., 1992)

Figure 22. Illustration of field measurements.

To capture canopy density, photographs were taken looking directly above points of interest and an onsite judgment was made to categorize the cover as heavy, moderate, light or none. Although the camera settings remained the same for each overhead picture, since the focal area varied from point to point, the pictures were not used to perform statistical comparisons. However, the pictures can provide a sense of vegetation type at each point. While the extreme heights of the canopies were measured, this information was found to be of minimal value for this experiment.

Trail edge characteristics, to include vegetation density, ground make-up and slope were documented. The vegetation density classification categories were the same as those used to categorize canopy densities (Heavy, Moderate, Light or None). The ground type for both the trail and trail edges was documented for any points falling on trails.

B. STATISTICAL METHODOLOGY

As noted in Chapter III, target and control points were randomly generated from cropped target and control areas respectively. A modified simple random sampling pattern was used to determine target and control points for this research. Multiple factors were taken into consideration to determine the sampling size for each area analyzed. It was necessary to balance the requirement for enough points for a statistically sound sample size with the available time and resources to accomplish adequate field sampling.

"In spite of efforts by various researchers, there is still no hard and fast rule for determining the number of samples needed for accuracy assessment." (McCoy, Field Methods in Remote Sensing) The "rule of thumb" from Congalton (1991) to use a minimum of 50 samples per category and 75-100 samples per category for larger areas was the starting point for each area. Congalton also notes that the number of samples for each category may be adjusted based on the relative importance of that category for the application. (Congalton, 1991)

The size of the cropped target areas and the total number of points included in those areas were then taken into account for determining how many random points would be generated (i.e., the greater the area and number of points, the greater the number of

random points generated). The number of control points selected for each area was approximately two-thirds the number of target points. The importance of positive identification of roads and trails compared to identifying areas where roads and trails do not exist was the reason for choosing a smaller number of control points.

The accuracy analysis for this research is based on the use of error matrices (also known as confusion matrices or contingency tables). Table 7 is an example matrix similar to those created from this research:

EXAMPLE ERROR MATRIX				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	**User Accuracy**
Trail	**80**	30	110	73%
No Trail	20	**70**	90	78%
Column Total	100	100	200	
Producer Accuracy	80%	70%		
		Overall Accuracy	**75%**	

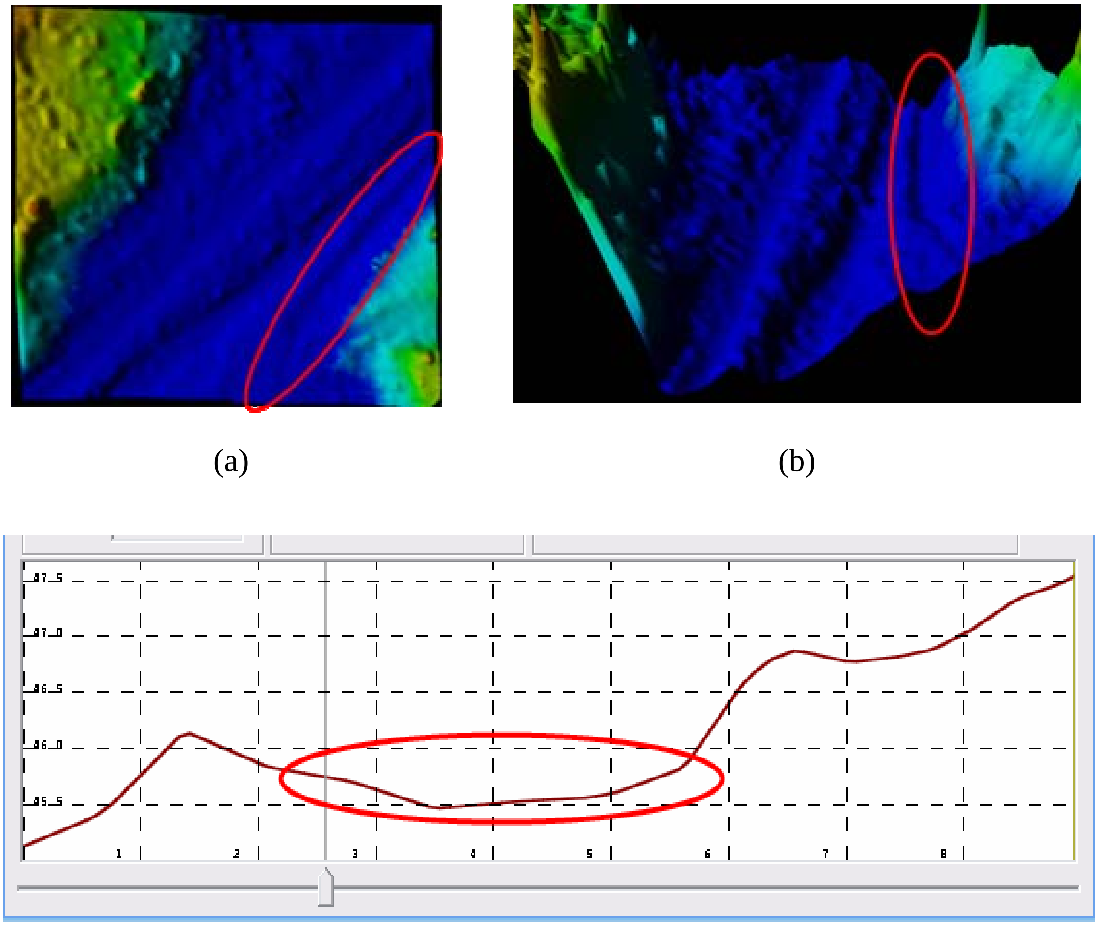
Table 7. Example Error Matrix.

The points generated in this research are classified in two categories, those falling on a trail (trail) and those not falling on a trail (no trail). The main diagonal of the error matrix (highlighted gray in the example) represents the points correctly classified through viewing of Lidar models. The rows represent the "classification data" and produce what are called user accuracies. User accuracies are calculated by dividing the number of points correctly classified by the total number of points classified in that category. In the example, for every point identified as falling on a trail by viewing the Lidar data (target point), there is a 73 percent chance that point actually falls on a trail. Similarly, there is a 78 percent chance that each control point identified will not fall on a trail. The columns in this example represent the "reference data" and create producer accuracies. Producer accuracies are calculated by dividing the number of points correctly classified for that category by the total number of points actually in that category (as verified through ground truth efforts). For all the points (target and control) that actually fell on trails in the sample above, 80 percent were correctly classified as trail (target points) from viewing Lidar models. Seventy percent of all points not falling on trails were correctly

classified. Perhaps the simplest but not necessarily the most useful information from these matrices is the overall accuracy. The overall accuracy is calculated by dividing the total number of points correctly classified by the total number of points. In other words, 75 percent of all the points analyzed (target and control) were correctly classified.

C. OBSERVATION AND EVALUATION TECHNIQUES

In cases where there is enough poke-through (ground point density), the visible characteristics on a Lidar surface model for trails under canopy are the same as for those not under canopy. When viewing surface models, the most obvious characteristic is trail depression (Figure 23a). The depression can be further exaggerated by stretching the model with the “rescaling model height” tool (Figure 23b). Additionally, the “height profile” tool can be utilized to obtain detailed characteristics and measurements of the trail depression by providing a cross section of the trail (Figure 23c).

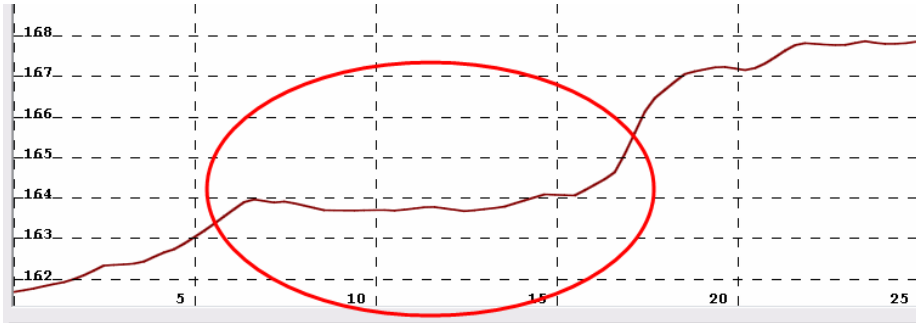


(a) (b)

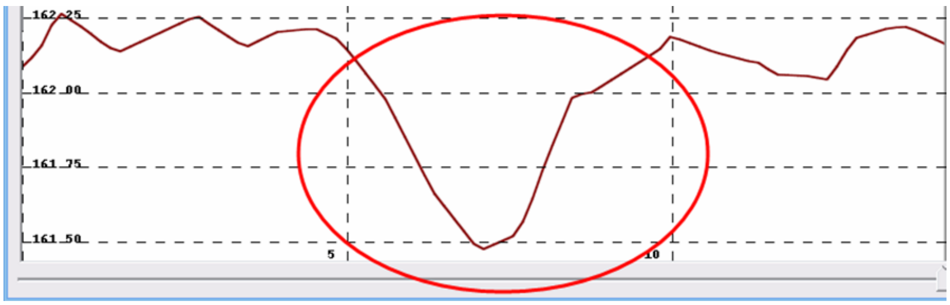
(c)

Figure 23. Lidar Trail Characteristics for Kahuku Site 4: (a) Surface Model initial top view, (b) Surface Model tilted and Height Exaggerated, (c) Height Profile across Trail

Several characteristics can be used to determine if a depression is a man-made trail or other natural feature, such as drainage erosion or terraces. Figure 24 shows the height profile across a road as compared to across a natural drainage depression. The road appears flat across the traveled way, where the drainage depression appears to have a "V-shape." This indicates vehicles have not traversed the depression.



(a)

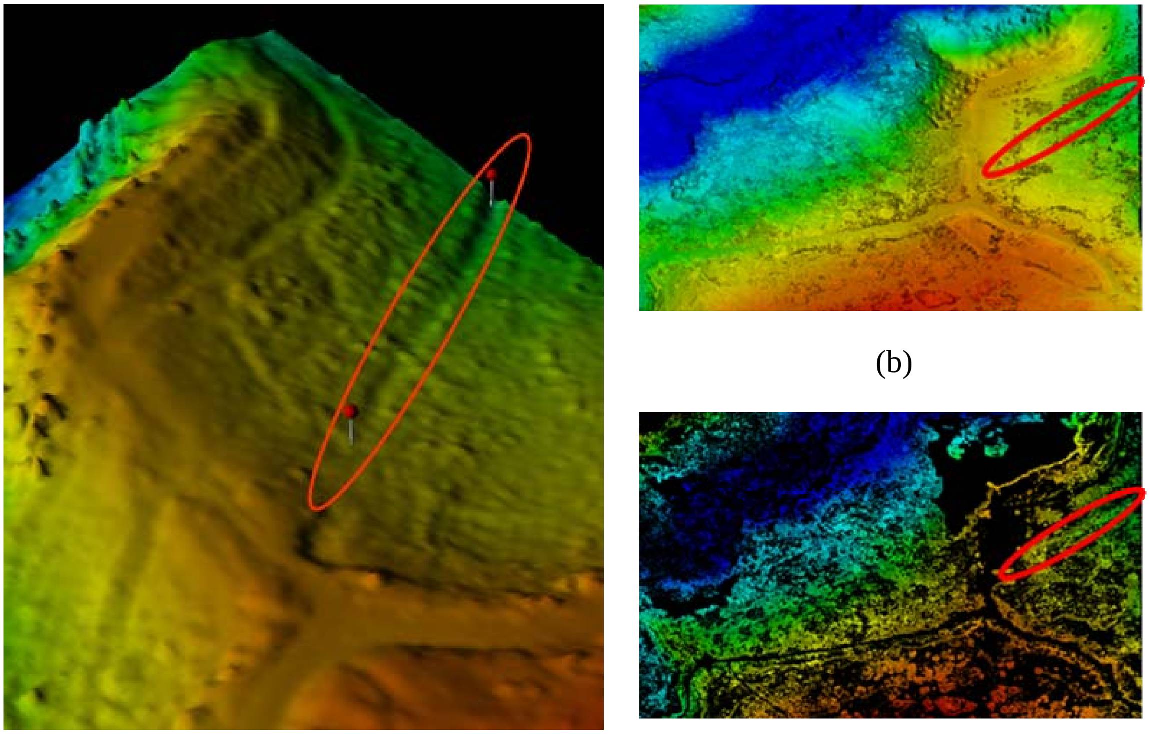


(b)

Figure 24. Height profiles of (a) Kahuku Road and (b) Kahuku natural drainage depression

Distinguishing between trails and natural drainage areas is more difficult and requires further evaluation of additional features. Using the height profile tool along the trail can provide indications of trail roughness and other obstructions.

Overlaying the object file (clipped at one meter AGL) over the surface model is another method that can be used to differentiate between man-made and natural depressions. Doing this can provide indications of obstacles such as vegetation or other obstacles in the depression (Figure 25). Another method is to view the object file without the surface model underneath. Clipped at one meter (waist high), trails created by vegetation cleared for human traffic will tend to show up as linear gaps in the object file, Figure25c.



(b)

(a) (c)

Figure 25. Kahuku Site 6 (a) Surface File, (b) Surface File with Object File overlaid, and (c) Object File only.

There are a few things to consider when identifying roads or trails under canopy. The first is that highly traveled, unpaved roads and trails will exhibit a clear continuous linear depression. An example of this is the trails found in Cougar Mountain; trails that either by park design and maintenance or through heavy traffic were clearly visible when viewing surface models. In most cases, the traveled way will be narrower than the visible depression. This can be due to the type of traffic (vehicular or foot) through the depression, the level of traffic, the type of vegetation, trail ground composition, or intentional human modifications.

Concerning vehicle depression on unpaved roads, further evaluation is required to determine if height profiles are useful for identifying the type of vehicular traffic that routinely access them (i.e., tanks, trucks, etc.). In other words, the widths of the depressions made by wheeled or tracked vehicles and the separation between them might

be enough information to classify the type of vehicles traveling on that road. The slope and radius of turns in the road can be viewed in Lidar models and may provide additional indications of the accessibility to different types of vehicles.

There will be times when the entire road or trail will not be identifiable, due to lack of depression, point density, or limited trail width. In these cases, the analyst will have to decide whether there is enough evidence to determine how or if the missing portion of a trail connects to the other two sections, (Figure 26). During this experiment, missing portions of roads or trails were not included in the target areas. Only portions of the trails visible in the Lidar models were identified as trails.

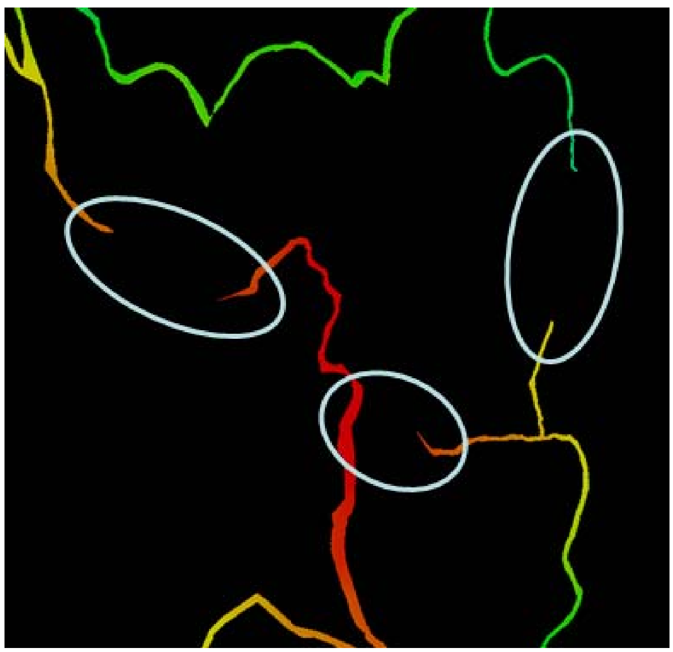


Figure 26. Example of trail cropping showing missing portions of trails.

Perimeters of the surface models must be closely scrutinized. During the analysis, it was observed that some trails were missed because the trail was close to the perimeter of the data set leaving only a small portion of the trail. This limited the ability to queue the linear features of the trails (Figure27).

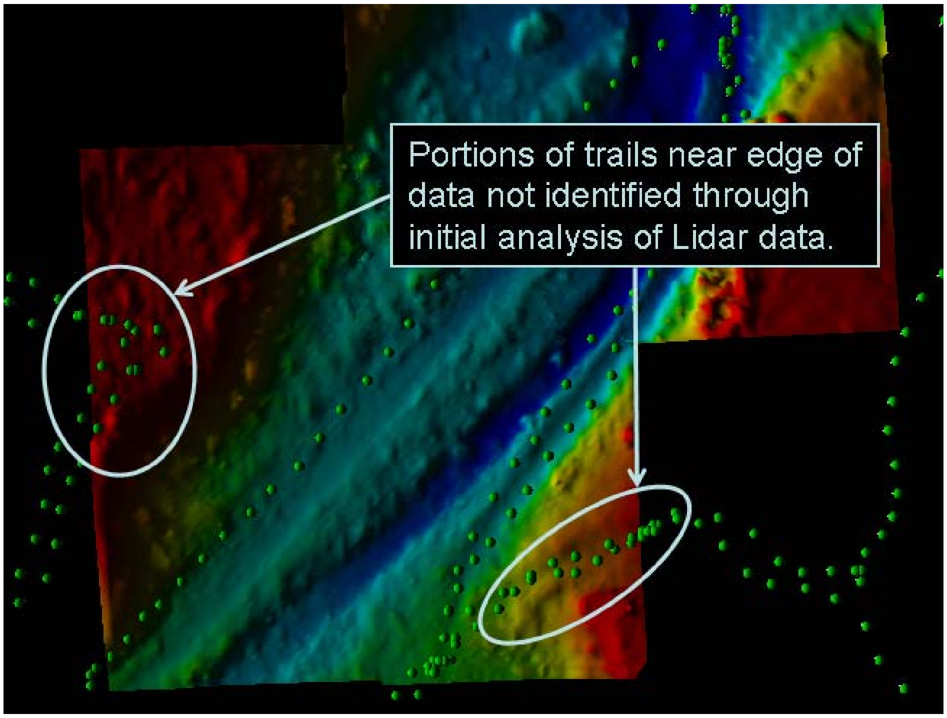


Figure 27. Kahuku Site 3 & 4 missed trails near edge of data set. The green pins represent GPS track log points of trails walked during ground truth verification site visit.

D. LIDAR ARTIFACTS

When viewing surface models, Lidar artifacts will be quite evident to the analyst. Some of the artifacts encountered while conducting this research and potential causes are explained below. As will be clearly visible in the following examples, areas high in artifacts are of little use when attempting to identify trails hidden under canopy.

1. Crystal Forest or Pyrite Forest

"Where there are few survey points (i.e., bare-earth surfaces in heavy timber, where there are few ground reflections), TINning the points produces large triangular facets where the surface has significant curvature. Similar, though finer, textures are evident where vegetation reflections are incompletely filtered. Elevations are likely to be less accurate in these areas." (PSLC, 2005)

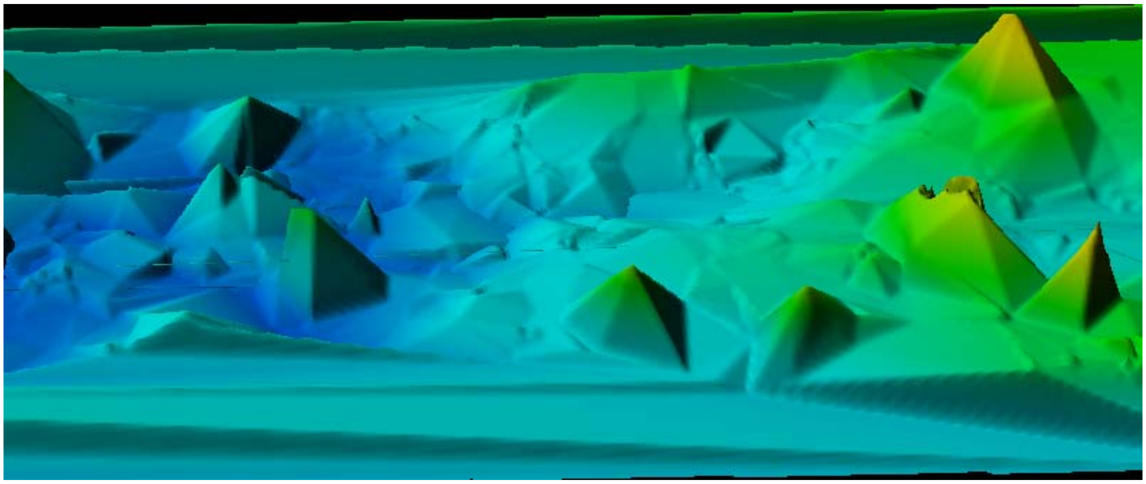


Figure 28. Example of crystal forest artifact.

2. Bomb Craters

"Most Lidar data sets contain scattered too-low points, or negative blunders, perhaps produced when a specular reflection or too-close ground saturates the detector and produces an internal echo. If vegetation reflections are removed by a find-the-lowest-point-in-the-vicinity algorithm, true ground points adjacent to the negative blunders may be misidentified as vegetation reflections and removed. The result can be a conical crater that is entirely an artifact." (PSLC, 2005)

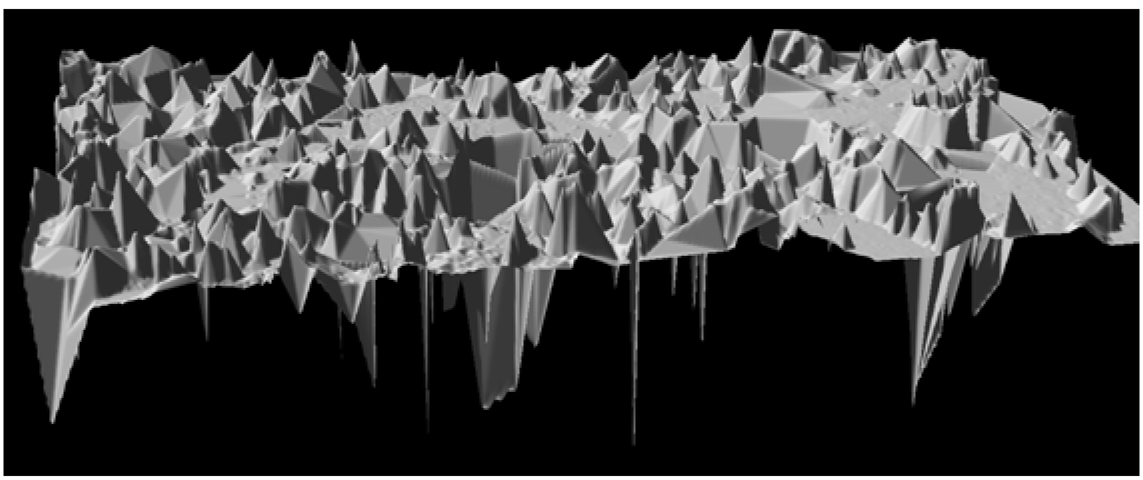


Figure 29. Example of bomb crater artifact.

V. ANALYSIS

This chapter provides detailed descriptions of the statistical analysis for each site evaluated in this research. Although no statistical analysis was performed for the Elkhorn Slough site, a detailed description of how it was utilized as a training site is provided. Sample size selection, error matrices, elevation comparison graphs and explanations of each are included for the remaining three sites. Since the focus of this research was to identify trails under canopy, the error matrices presented in this chapter represent only those points classified as under canopy through analysis of Lidar point cloud models. Due to the elapsed time between time of collection and site visits, the Lidar data was used to determine if a point was under canopy rather than ground truth verification. Appendix B contains every error matrix created; representing all target and control points including sub-site breakdowns for Kahuku and La Selva.

A. ELKHORN SLOUGH

Elkhorn Slough, the first site evaluated, was an ideal training site to outline research methods used throughout this project due to its close proximity to the Naval Postgraduate School. In addition to refining a collection strategy for following site visits, the Elkhorn Slough training site provided a means for familiarization with Lidar software, GPS data transfer techniques, differing coordinate systems and database management techniques. Most importantly, this site provided positive early indications of the feasibility for using Lidar to identify roads and trails under canopy. The Elkhorn Slough objectives are listed in Table 8:

Elkhorn Slough Objectives	Chapter-Section Reference
Develop data analysis processes and techniques	IV
Gain proficiency with Quick Terrain and GPS software.	APP-D / E
Develop field procedures	III-A, IV-A
Establish sampling strategy	III-A
Develop classification methodology	IV-A
Develop accuracy assessment procedures	IV-B
Determine trail characteristics to be recorded	IV-A

Table 8. Elkhorn Slough Objectives

Trails under canopy in the Elkhorn Slough are limited and most are clearly identifiable using overhead imagery. Nevertheless, trail segments can be found that periodically fall under canopy. A number of target trails and roads under canopy were selected for the sole purpose of collecting ground truth information for those areas. This information was then compared to Lidar surface models to determine if selected trails were apparent through visual inspection. Overlaying the object and point cloud files over the surface model confirmed the presence of canopy over selected trail segments when the data collection occurred (Figure 30b).

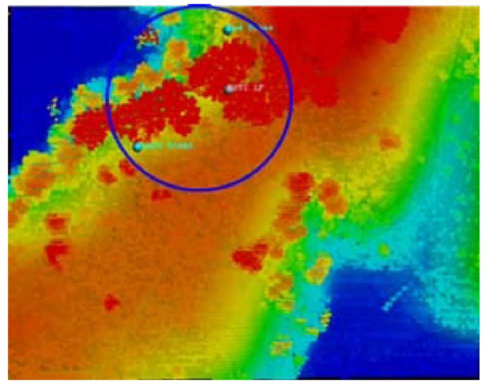
The Elkhorn Slough observations may seem rather basic, but with no previous research found on the subject, the ability to follow trails in and out of the canopy provided an early comparison of overhead imagery, ground truth and 3-D Lidar models. In other words, the trail segment was verifiable by all observation methods. The short trail segments under canopy allowed for comparison of covered and uncovered trails. This provided initial clarification of trail characteristics identifiable on Lidar surface models.

The images in Figure 30 represent an example of one trail segment initially evaluated at Elkhorn Slough. The trail segment under canopy was approximately 30 meters long and 4 meters wide. Evaluation of this and other selected trail segments in the Elkhorn Slough area provided evidence that it is possible to identify trails under canopy

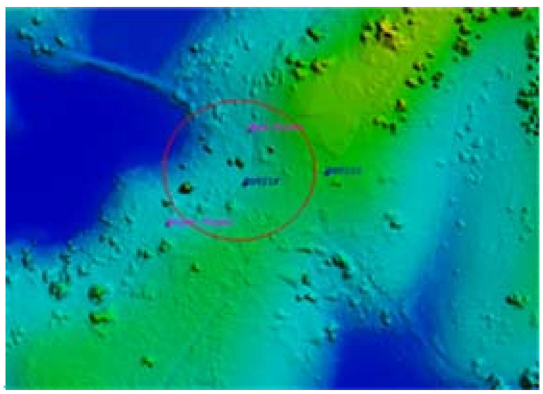
using Lidar. Following this assessment, it was determined that a collection strategy was required to document and quantify trail identification accuracy.

Although no statistical results were calculated for this site, the Elkhorn Slough objectives stated earlier were met. As a training site, Elkhorn Slough was invaluable, providing the experience necessary to carry out a systematic approach in the planning and execution of the data set analysis that followed.

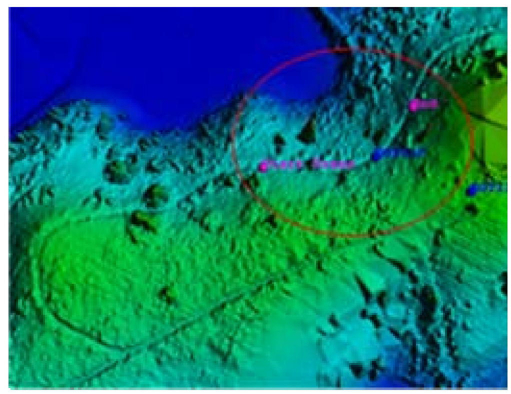
(a)



(b)



(c)



(d)

(e)

(f)

Figure 30. Elkhorn slough evaluated trail: (a) Overhead image of Eucalyptus tree stand (From: Google Earth), (b) Lidar model (all points), (c) Surface model (no alterations), (d) Surface model (Rescaled Height), (e) Covered trail entrance, (f) Trail canopy

B. KAHUKU

Kahuku was the first site analyzed using the accuracy assessment strategy described in Chapter IV. The Kahuku data is the most recent (2005) collected of the four sites analyzed in this experiment. This sensor was mounted onboard a rotary wing aircraft to simulate the step-stare technique described in Chapter II. This collection method provided multiple look angles, increasing the probability for pulses to poke through gaps in the canopy and reach the surface below. The area consisted of seven sites as described in Chapter III. Site 7 was not accessible for ground truth verification due to ongoing training during the time of the site visit.

The sample sizes initially selected for the entire Kahuku site consisted of 197 target and 115 control points. The sample sizes reduced to 157 target points and 104 control points following adjustments made for points falling within five meters of each other. Points were removed during the ground truth verification to reduce the bias caused by counting multiple points representing the same general area. The site-specific breakdown of target and control point is found in Table 9. The large number of points selected for Site 6, compared to the other sites, is the result of it being a much larger area and the large target area resulting from the many possible trails classified during the Lidar analysis.

KAHUKU TARGET & CONTROL TEST AREA STATISTICS						
	Approximate Target Area (m^2)	Target Sample Size Selected	Target Sample Size (after points removed)**	Approximate Control Area (m^2)	Control Sample Size Selected	Control Test Points (after points removed)**
Site 1	750	8	7	822	5	5
Site 2	2,548	26	18	2,555	18	13
Site 3	1,770	18	13	1,850	12	10
Site 4	2,915	30	20	3,037	20	18
Site 5	1,430	15	10	1,500	10	9
Site 6	32,230	100	89	32,210	50	49
Site 7						
TOTAL	41,643	197	157	41,974	115	104
** Removed for randomly generated points falling within 5 meters of another.						

Table 9. Kahuku target and control test area statistics.

The statistical analysis for Kahuku resulted in producer accuracies of 91 percent for both “trail” and “no trail” classification, user accuracies of 93 and 89 percent for “trail” and “no trail” classification respectively, and an overall accuracy of 91 percent

(Table 10). While these high percentages were very encouraging (especially for the first site evaluated with statistical analysis), it is important to note they are somewhat skewed because of the maintenance road traversing all of the sites analyzed. While the road is a valid "target" for analysis, its width compared to the width of the other trails caused the majority of the target points to fall on the road. Obviously, a 5-meter wide road is much easier to classify correctly than a 1.5-meter wide trail. Some changes were made for subsequent sites analyzed to help minimize this bias. These changes will be discussed in the following La Selva and Cougar Mountain sections respectively.

TOTALS FOR COVERED POINTS				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	100	8	108	93%
No Trail	10	79	89	89%
Column Total	110	87	197	
Producer Accuracy	91%	91%		
		Overall Accuracy	91%	

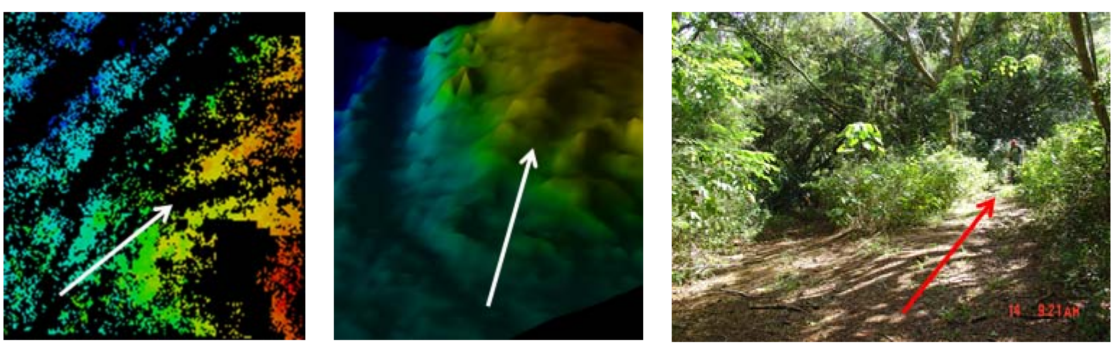
Table 10. Kahuku error matrix for points under canopy.

To determine how extensively the maintenance road affected the overall accuracy assessment, an error matrix was created excluding all points that where greater than 2.5 meters wide (Table 11). The removal of points classified as "road" resulted in the overall accuracy dropping to 85 percent. It should be noted that the removal of all "road points" actually shifts the bias in the opposite direction as there were fewer randomly generated points that fell on Cart Tracks and Trails due to their narrower widths. Nevertheless, the results are still very promising.

TOTALS FOR COVERED POINTS (Road Points Removed)				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	24	8	32	75%
No Trail	10	79	89	89%
Column Total	34	87	121	
Producer Accuracy	71%	91%		
		Overall Accuracy	85%	

Table 11. Kahuku error matrix for points under canopy with Road (width > 2.5m) target points removed.

The 8 points misclassified “trail” and 10 points misclassified “no trail” provided important lessons for future data analysis. Some of the points misclassified “no trail” fell on two separate trail segments in Site 4. Both of these trail segments fell near the edge of the data set. The first, branches off another trail, is not heavily traveled, does not have a large depression, and only a small segment is included in the data set. However, in hindsight, the segment is visible on the Lidar model and should have been identified (Figure 31). The second is a very narrow (less than one meter) trail falling on the other edge of Site 4 (Figure 32). It is hard to say whether this trail would be visible if more of the trail were included in the data. However, the small size and minimal depression of this trail make it extremely difficult to identify using this method without an extremely high ground point density. One lesson learned from this area is to use a high level of scrutiny while analyzing the edges of data sets as small segments of a trail may exist there with minimal linear depression to queue the analyst. Along the same lines, if collecting data specifically for the purpose of identifying trails (less than 1.5 meters), an adequate “buffer” area should be included around the AOI as additional trail information may provide visual queues for an analyst to find trail segments near the edges of the AOI.



(a) (b) (c)

Figure 31. Site 4 missed trail (marked by arrows): (a) object file, (b) surface model, and (c) photograph at ground truth

Figure 32. Picture of narrow trail missed at Kahuku Site 4.

Another group of points misclassified as "no trail" was found in Site 6. The trail identified by these control points was located on the floor of a very large canyon under very dense canopy (Figure 33). While the trail was relatively wide, it was not well traveled and had little to no depression. The only characteristic identifying it as a trail was the removed vegetation. There is no way to verify if this trail existed at the time of data collection. Either way, the situation identified a problem identifying trails cut out of vegetation and having little depression to provide a visual queue to an analyst viewing a Lidar surface model.

(a) (b)

Figure 33. Kahuku Site 6 missed trail.

The points misclassified "trail" were also from Site 6. These points represent an area identified by a linear depression in the surface model. Ground truth verification revealed this depression to be a dry riverbed overgrown with dense vegetation (Figure 34).

(a) (b)

Figure 34. Pictures of Site 6 area misclassified as trail.

While this was the only area in Kahuku with points misclassified as "trail," there were other areas with linear depressions causing them to appear as trails on the surface model. Natural terraces found at Site 6 provide a good example of this (Figure 35). Using other characteristics prevented misclassifying the terraces as trails. These situations identified the need for additional methods to verify if linear depressions are indeed trails.

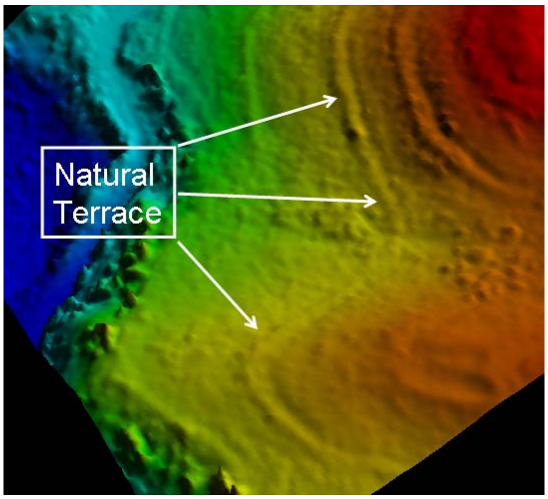


Figure 35. Site 6 surface model showing linear depressions caused by natural terraces.

Prior to the Kahuku ground truth site visit, the analysis of Lidar data relied exclusively on linear depressions in the surface models to identify trails. Following the issues identified at Site 6, the object file was identified as a possible solution to both problems. Specifying the AGL clipping to one or two meters provided additional information. Viewing the object file by itself can also provide visual queues to the existence of trails through linear gaps in the model where there is no vegetation at the specified AGL or below. While the missed trails at Site 6 still are not visible, this method was successful in helping identify trails in subsequent sites analyzed. Conversely, the object file can be used in a similar manner to determine the presence of dense vegetation or other obstructions that would prevent passage through a depression such as the one described in Chapter IV (Figure 25).

GPS tracklogs taken for every trail identified during the Kahuku ground truth site visit were used to perform comparisons between the elevations provided by the Lidar models and those recorded by GPS (as described in Chapter III). Figure 36 shows the elevation comparison for one trail in Site 6 and Figure 37 shows the tracklogs overlayed on a Google Earth image. Elevation comparisons for all remaining Kahuku trails are in Appendix C. The graphs for elevations provided by the two systems clearly trend one another for all the trails evaluated in Kahuku. It is important to remember elevation differences can be caused by horizontal error as described in Chapter II (Figure 9). Additional differences are a result of the GPS elevation being recorded from a backpack-mounted antenna approximately two meters above ground level.

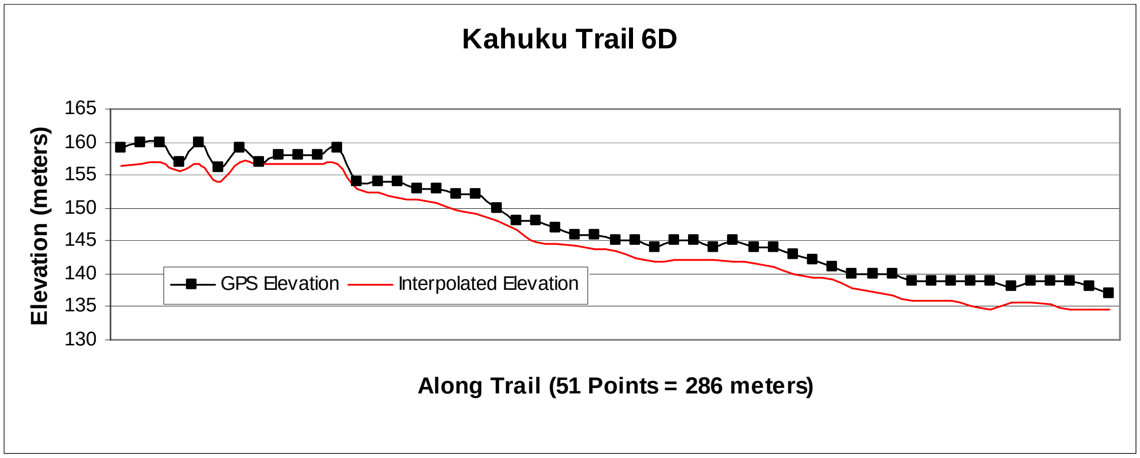


Figure 36. Elevation comparison for trail in Kahuku Site 6.

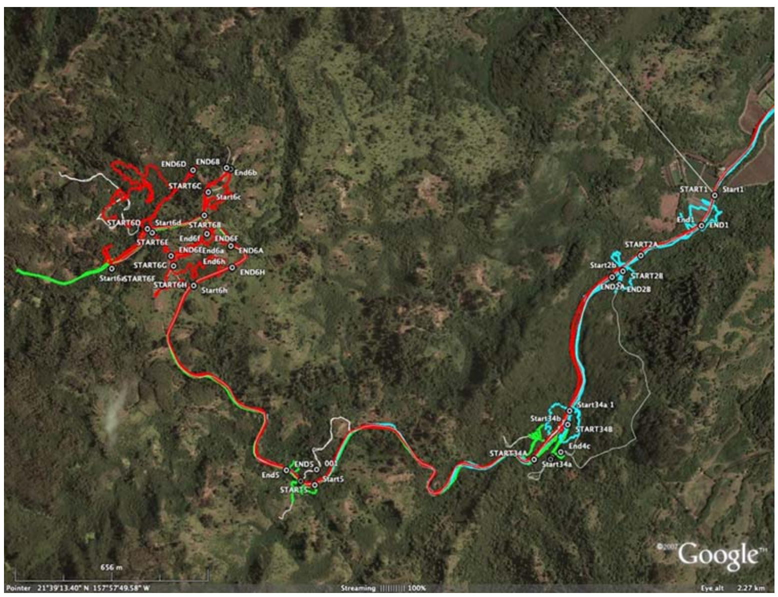


Figure 37. Kahuku Tracklogs of trails overlaid on Google Earth image. (After: Google Earth)

Figure 38 represents a correctly classified target point falling on a 2.5-meter wide trail in Kahuku. One target point on the trail is represented in the overhead imagery and corresponding Lidar models. Points from a GPS tracklog taken on the trail are also presented to show the x and y accuracies of the Lidar model. While there is a slight deviation (less than two meters) from the trail, there is no way to know definitively if this is caused by inaccuracies in the Lidar model or GPS error. Finally, ground truth

photographs provide an indication of the physical characteristics of the trail as well as the overhead canopy. As can be seen, the Lidar surface model accurately represents the trail underneath the canopy.

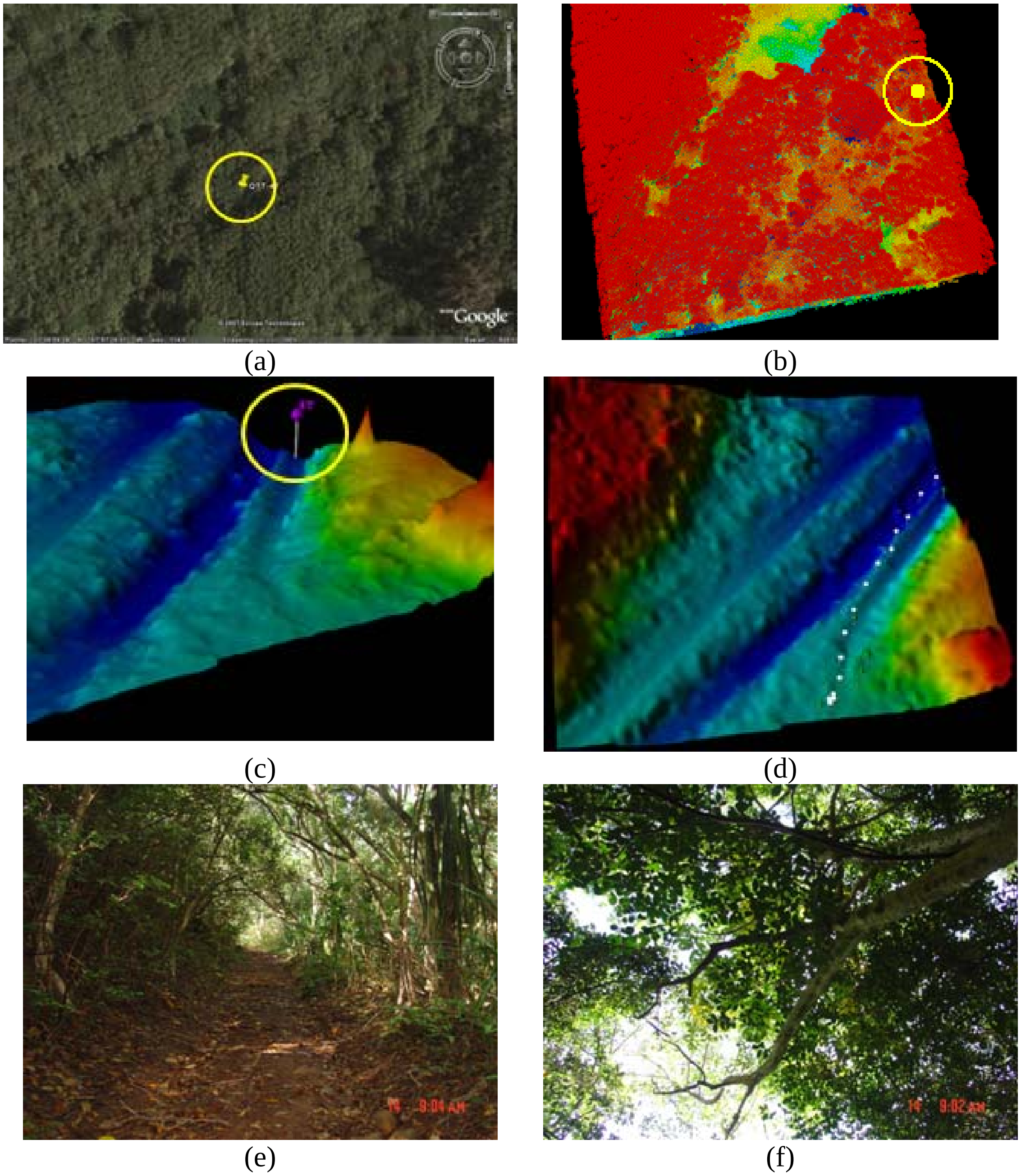


Figure 38. Kahuku target point example: (a) Overhead imagery (From: Google Earth), (b)Lidar all points, (c) Lidar surface model with target point, (d) Lidar surface model with GPS tracklog points (white)and target points (green), (e) Ground truth surface at target point (2.5 meters wide), (f) Ground truth canopy at target point.

C. LA SELVA

The La Selva data, also collected with a sensor flown onboard a rotary wing aircraft, is by far the oldest (1997) evaluated in this research. Although flown on a rotary wing aircraft, the La Selva platform did not utilize the collection methods used in Kahuku. Therefore, the multiple look angles mentioned for the Kahuku section above do not apply for this data set. The 10-year lapse between the data collection and ground truth verification created a number of challenges. One is the technology gap between the Lidar sensors of 1997 versus those available in 2000-2001 and 2005. Specifications of the sensor used for this data collection were not available at the time of writing, but it is expected that the sensor operated at approximately 8 kHz PRF (compared to today's sensors that can operate up to 250 kHz).

The La Selva data was initially received in two geographically separated areas referred to in this document as the La Selva and Alien Head areas (Figure 39). The Alien Head area is nicknamed for the appearance created by the rivers bounding the region on the east, west and northern edges. The initial size of the La Selva area was approximately 4 km x 1 km. The southwestern part of the data set, where the canopy is most dense, was determined to be unusable for locating roads or trails due to the surface model consisting entirely of Lidar artifacts described in Chapter IV. This unusable region consists of primarily old growth forest and represents some of the densest canopy found in the area (and the world). The inability of the Lidar pulses to poke through the canopy consistently is the most likely cause of the artifacts. This area reduced to approximately 1 km x 1 km of usable data. The Alien Head area was approximately 0.7 km x 0.4 km.

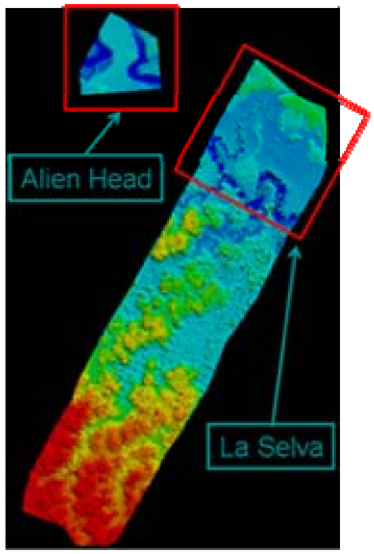


Figure 39. La Selva and Alien Head surface models.

The sample sizes initially selected for the entire La Selva site (including La Selva and Alien Head areas) consisted of 350 target and 224 control points. The sample sizes reduced to 185 target and 158 control points following adjustments made for points falling within five meters of each other. Additional code, written into the random point generation program, automatically removed points falling within five meters of another point based on lessons learned from the Kahuku site visit. The site-specific breakdown of target and control points is in Table 12.

LA SELVA TARGET & CONTROL TEST AREA STATISTICS						
	Approximate Target Area (m^2)	Target Sample Size Selected	Target Sample Size (after points removed)**	Approximate Control Area (m^2)	Control Sample Size Selected	Control Test Points (after points removed)**
La Selva	53,078	250	132	54,536	160	106
Alien Head	19609	100	53	20463	64	52
TOTAL	72,687	350	185	74,999	224	158
** Removed for randomly generated points falling within 5 meters of another.						

Table 12. La Selva Target and Control Test Area Statistics

The statistical analysis for La Selva points that fell under canopy resulted in producer accuracies of 93 and 71 percent for “trail” and “no trail” classifications respectively, user accuracies of 67 and 94 percent for “trail” and “no trail” classifications respectively, and an overall accuracy of 80 percent (Table 13). Similar to Kahuku, a road ran through the La Selva test area. In order to reduce the bias created by a majority of

target points falling on the road, all trails were cropped to approximately the same width regardless of their actual width on the data set. The cropping is a manual process, so obviously the width of the cropping was still not exactly uniform for all trails.

TOTALS FOR COVERED POINTS				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**84**	41	125	67%
No Trail	6	**99**	105	94%
Column Total	90	140	230	
Producer Accuracy	93%	71%		
Overall Accuracy			**80%**	

Table 13. La Selva Error Matrix for points under canopy.

As with Kahuku, an error matrix was created excluding all points correctly classified that were greater than 2.5 meters wide (Table 14). The removal of these points reduced the overall accuracy from 80 to 76 percent. The greatest effect is seen in the user accuracy for points classified as "trail." This is because 43 percent of the target points correctly classified as targets were removed. Even with the removal of the points classified as "Road" points, the accuracy achieved is still very promising.

TOTALS FOR COVERED POINTS (Road Points Removed)				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**48**	41	89	54%
No Trail	6	**99**	105	94%
Column Total	54	140	194	
Producer Accuracy	89%	71%		
Overall Accuracy			**76%**	

Table 14. La Selva Error Matrix for points under canopy with Road (width >2.5 m) target points removed

"In some projects the time between the project beginning and the accuracy assessment may be so long as to cause temporal problems in collecting ground reference data. In other words, the ground may change (i.e., the forest harvested) between the time the project is started and the accuracy assessment is begun." (Congalton, 1991) The 10-year difference between the data collection and ground truth verification for the La Selva

data set would certainly qualify as one of those projects. One would expect a lot to change over this long period; especially in a jungle environment with the amount of rainfall received in the Costa Rican rain forests. As evidenced in the error matrix above, 41 points under canopy were misclassified as “trail” during the analysis of the Lidar models. During ground truth verification, many of these misclassified points were found overgrown with vegetation. However, in some cases, these same points fell near abandoned, man-made structures implying there may have previously been trails in those areas (Figure 40). With no method to verify whether the trails were active during data collection, these points were counted as misclassified for statistical purposes.

Figure 40. Abandoned picnic area restrooms in La Selva.

An elevation comparison was accomplished for a representative trail in the Alien Head test area (Figure 41). A significant discrepancy is found between the elevations derived from the Lidar models and those recorded by GPS. The differences in elevation are generally 12 to 15 meters but deviate as much as 22 meters at one point. An interesting characteristic of this discrepancy is that the Lidar data consistently represents a much lower elevation than the GPS measurements. If the opposite were true, an obvious explanation could be that the Lidar pulses were not reaching the ground due to

the dense vegetation. While little information could be found for the sensor used for this data collection, it seems pertinent to mention that information found for a Lidar collect of the same area in 1998 by another organization mentioned a problem with technology at the time causing inaccurate elevation values.

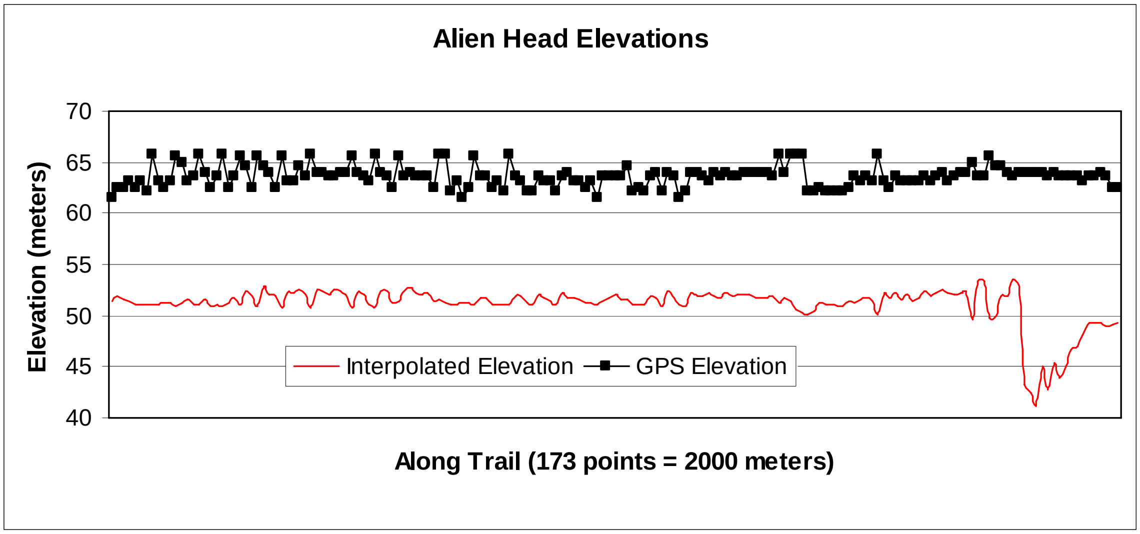
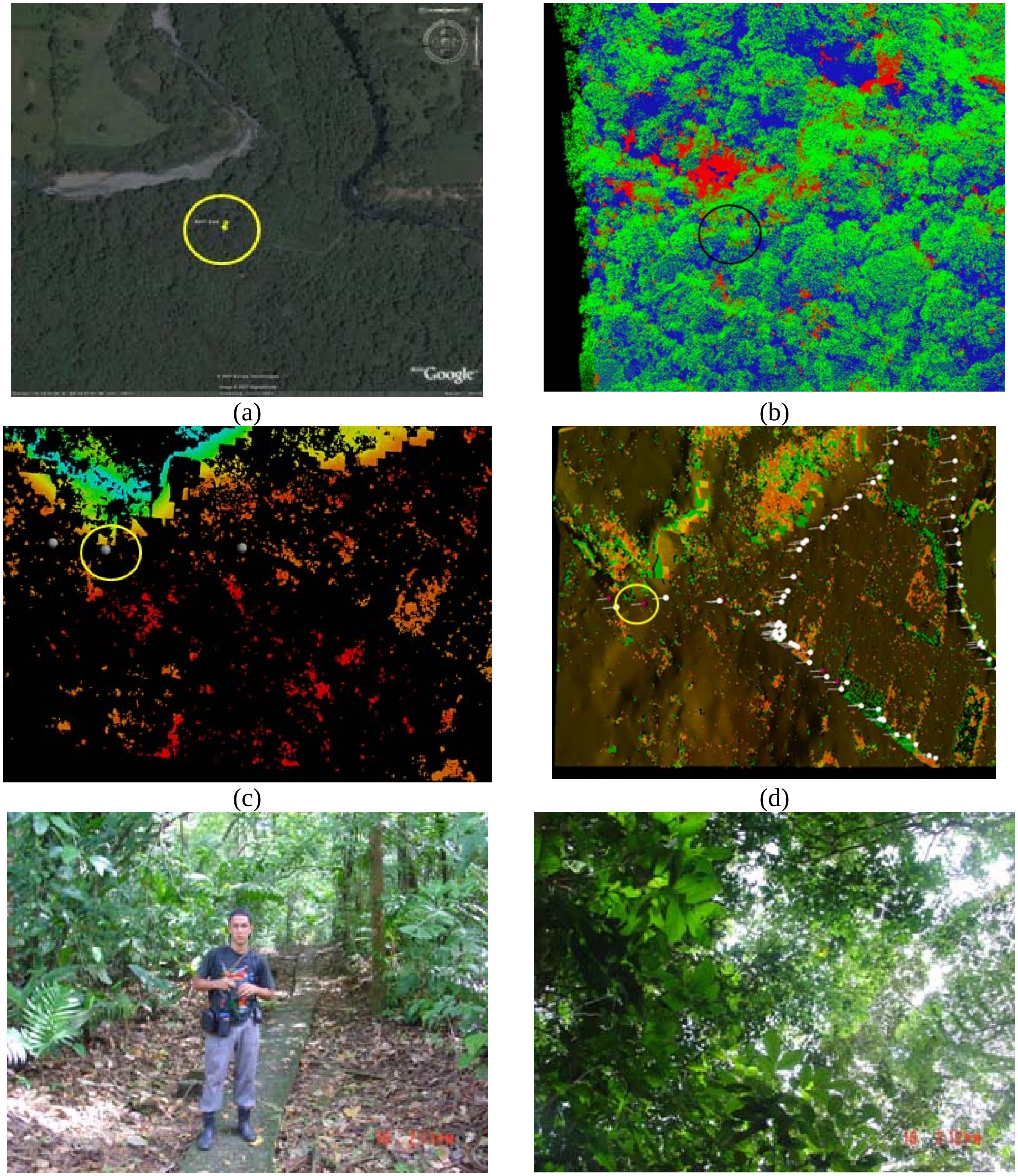


Figure 41. Elevation comparison for tracklog from Alien Head test area.

Similar to the Kahuku figures seen earlier, Figure 42 is an example of a correctly classified trail in La Selva with a traveled way 0.7 meters wide and an extreme width of 3.2 meters. Overhead imagery and corresponding Lidar models provide an idea of the canopy covering that area (specifically the target point identified). The primary difference between this example and the one seen in the Kahuku example is that for this particular trail, the lack of returns in the object file (AGL = 2 meters) was the primary method for identifying the trail vice the linear depression clearly visible in the Kahuku example. Again, points from a GPS tracklog taken on the trail are presented to show the x and y accuracies of the Lidar model. Ground truth photographs represent the physical characteristics of the trail and overhead canopy.



(a) (b) (c) (d) (e) (f)

Figure 42. Alien Head target point example: (a) Overhead imagery (From: Google Earth), (b)Lidar all points, (c) Lidar object model with target point, (d) Lidar surface and object models with GPS tracklog points (white)and target points (pink), (e) Ground truth surface at target point (traveled way width 0.7 meters), (f) Ground truth canopy at target point.

The relatively old technology and 10-year delay discussed above greatly limited the ability to identify specific factors contributing to misclassified points. The massive tree heights (some over 50 meters) and high percentage canopy closures (up to 99%) make La Selva an extremely difficult area for this application. On the other hand, these features, combined with the extensive trail network in the area, make La Selva an ideal location for future research and testing. This location is easily accessible for field research and simulates the most challenging operational environment expected to be encountered.

D. COUGAR MOUNTAIN REGIONAL WILDLAND PARK

The Cougar Mountain data set was collected in January 2001 onboard a fixed-wing aircraft. Unlike the other sites, Cougar Mountain provided an area where the entire trail network was under canopy. Additionally, it is a trail network designed with widths suitable for pedestrian and equestrian traffic rather than motorized vehicles. The test area selected, shown in the boxed area of Figure 19, is approximately 3.5 km x 2 km.

The sample sizes initially selected for Cougar Mountain consisted of 250 target and 160 control points. The sample sizes reduced to 161 target and 101 control points following adjustments made for points falling within 10 meters of each other. The random point generation program was modified to remove points falling within 10 meters of another point automatically to further mitigate statistical bias caused by counting multiple points representing the same area. Twenty-five additional target points were removed from the sample set because they fell in an area set aside for habitat conservation off limits to the public. Therefore, ground truth verification of these points was not possible. The breakdown of target and control points is in Table 15.

COUGAR MOUNTAIN TARGET & CONTROL TEST AREA STATISTICS						
	Approximate Target Area (m^2)	Target Sample Size Selected	Target Sample Size (after points removed)**	Approximate Control Area (m^2)	Control Sample Size Selected	Control Test Points (after points removed)**
Cougar Mountain	47,800	186	161	48,100	101	101
** Removed for randomly generated points falling within 10 meters of another.						

Table 15. Cougar Mountain target and control test area statistics.

The statistical analysis for Cougar Mountain points under canopy resulted in producer accuracies of 90 and 64 percent for “trail” and “no trail” classifications respectively, user accuracies of 67 and 89 percent for “trail” and “no trail” classifications respectively, and an overall accuracy of 76 percent (Table 16). In addition to the pedestrian and equestrian trail network, the Cougar Mountain test area contained an access road, parking area and open clay pit clearly visible in the overhead imagery. A decision was made to remove these areas from the test area completely for the following reasons: 1) to eliminate statistical bias caused by large percentages of target points falling on the road, and 2) to concentrate research on trails under canopy.

COUGAR MOUNTAIN (COVERED POINTS)				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**104**	51	155	67%
No Trail	11	**90**	101	89%
Column Total	115	141	256	
Producer Accuracy	90%	64%		
Overall Accuracy			**76%**	

Table 16. Cougar Mountain Error Matrix for points under canopy.

Once again, an error matrix was created excluding all target points correctly classified that where greater than 2.5 meters wide (Table 17). The overall accuracy for this site only dropped by two percentage points. The minimal change reflects the fact that the trails in this area are designed for pedestrian and equestrian use only. It is also a result of the maintenance road being removed from the data set prior to trail classification.

TOTALS FOR COVERED POINTS (Road Points Removed)				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**86**	51	137	63%
No Trail	11	**90**	101	89%
Column Total	97	141	238	
Producer Accuracy	89%	64%		
Overall Accuracy			**74%**	

Table 17. Cougar Mountain Error Matrix for points under canopy with Road (width > 2.5m) target points removed.

One major modification to the ground truth verification strategy was required to ensure personnel safety and compliance with park regulations. As discussed in Chapter III, Cougar Mountain, formerly a coal mining area, contains many abandoned mines off the marked trails. Park regulations prohibit accessing areas located off the mapped trails due to hazards including cave-ins, steep slopes and toxic fumes associated with past mining activity. (*King county department of natural resources and parks.*2007) Target or control points falling more than seven meters off marked trails, as determined using the GPS handheld units, were evaluated as "no trail" for statistical purposes.

Two geographically separated control areas were selected within the Cougar Mountain test site. Mapped trails not visible on the Lidar models were identified traversing each of these areas. These trails represent the 11 points misclassified as "no trail" in the error matrix above. One of the missed trails was 0.87 (Figure 43a) meters wide and the other 1.2 meters wide (Figure 43b). The trails exhibit little depression representing the traveled way. Additionally, the traveled way also represents the extreme width of the trail and therefore provides no additional identifying characteristics. Since the collection was flown to achieve a 1.5-meter resolution, it is reasonable to assume that both the lack of a significant depression and narrow width of the depression would not be captured by the bare earth algorithm.

(a)

(b)

Figure 43. Cougar Mountain missed trails: (a) 0.87 meter wide trail, (b) 1.2 meter wide trail

The inability to access target points misclassified as “trail” hindered the ability to further scrutinize the region and determine characteristics that may have led to the misclassification. One of these sections containing five misclassified target points was partially visible from the trail. The area appeared to be a “side hill out,” approximately five meters wide, which may have previously been used as a mining road. (Figure 44) Unfortunately, it is impossible to make that determination without physically accessing the entire area to verify each individual point.

Figure 44. Cougar Mountain point misclassified as “trail.”

Four sections of trails were chosen to perform elevation comparisons between the Lidar models and those recorded with the GPS tracklogs. Figure 45 shows one of these comparisons (the rest are available in Appendix C). Generally, the GPS elevations and the Lidar models trended one another closely. The differences in elevation range from approximately 2 to 12 meters. Based on the erratic changes of the GPS elevations where the differences are the largest, it is suspected that the major differences in these areas are due to GPS errors as opposed to the Lidar models.

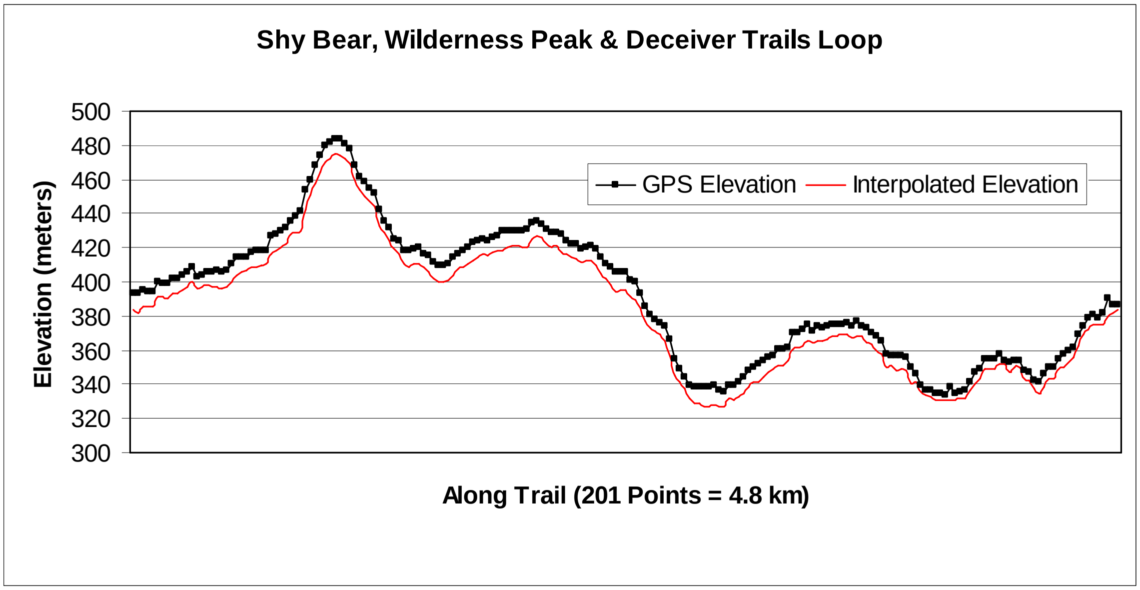


Figure 45. Cougar Mountain Shy Bear, Wilderness Peak and Deceiver Trail elevations.

Figure 46 is an example of a correctly classified trail in Cougar Mountain with a traveled way 0.9 meters wide. Once again, overhead imagery and corresponding Lidar models provide an indication of the canopy covering that area. This area provides an excellent example of the linear depressions used to identify trails from a surface model and shows how closely the GPS tracklog points taken from that trail follow along the depression. Ground truth photographs are provided to convey the physical characteristics of the trail and overhead canopy.

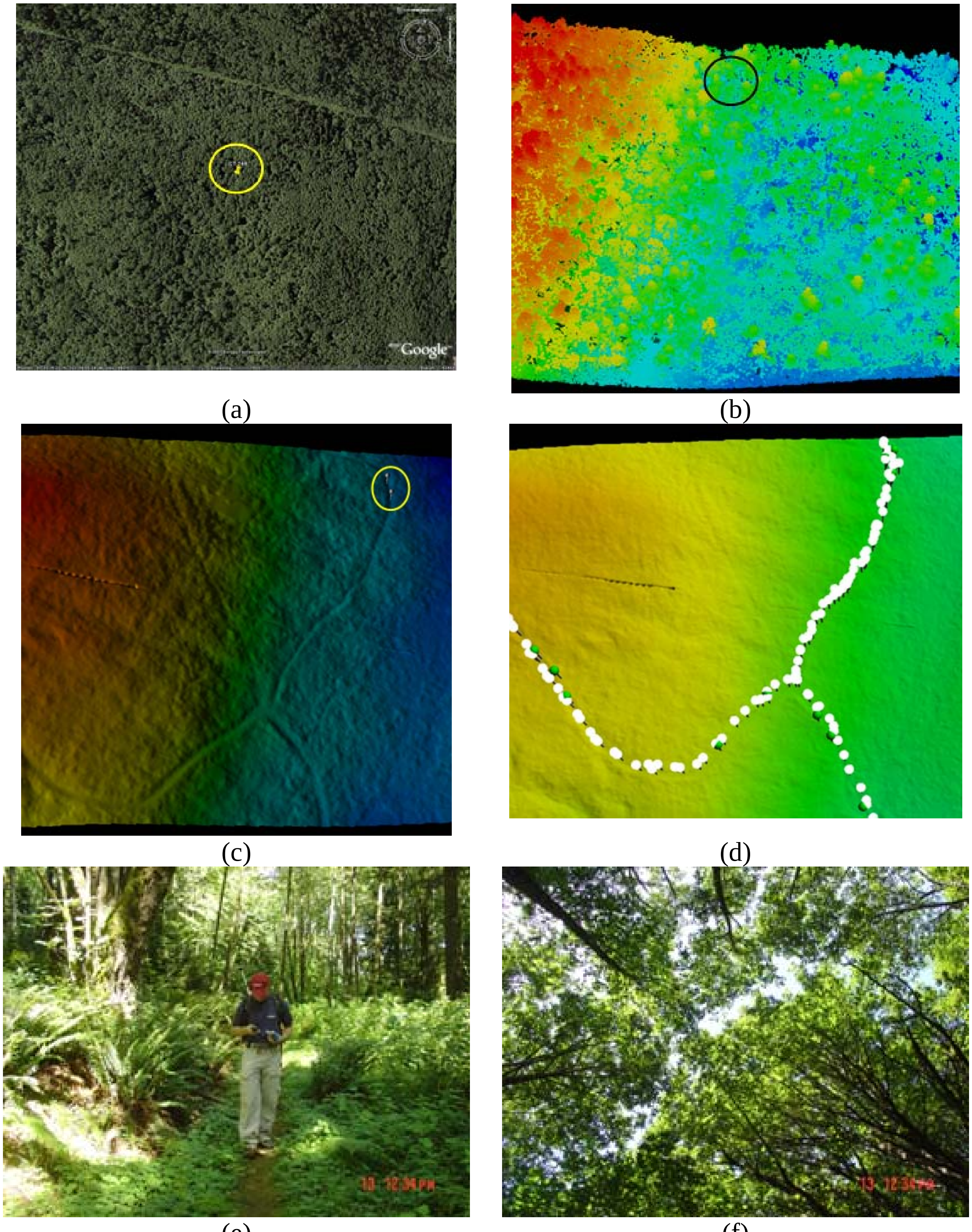


Figure 46. Cougar Mountain target point example: (a) Overhead imagery (From: Google Earth), (b)Lidar all points, (c) Lidar surface model with target point, (d) Lidar surface model with GPS tracklog points (white)and target points (green), (e) Ground truth surface at target point (traveled way 0.9 meters wide), (f) Ground truth canopy at target point.

VI. SUMMARY

A. THESIS RESULTS

The overall results of this experiment represented by the statistical analysis (Chapter V) are very encouraging. A few factors need to be discussed in further detail. As discussed earlier, all three sites included in the statistical analysis contained a road passing through the evaluated sites. While the primary road was removed from the Cougar Mountain data prior to analysis, the roads in Kahuku and La Selva made up a large percentage of the target points under canopy correctly identified through Lidar analysis (Figure 47). This is especially true in Kahuku and La Selva where these roads played a major role in the high accuracy percentages obtained for those sites. This is the reason that additional error matrices were created with correctly classified points that fell on roads greater than 2.5 meters wide removed. One observation to take away is that roads greater than 2.5 meters wide have a high probability of being detected and correctly classified using Lidar models. Although the accuracy results dropped when the target points falling on roads were excluded, the percentages still significantly surpass any capabilities offered by current alternative sensors. One subtle point to take away is that in areas such as Kahuku and La Selva where trail networks were not planned or designed to accommodate certain types of traffic (e.g. equestrian, foot-traffic) as in Cougar Mountain, the narrower tracks and trails generally branch off the wider lines of communication (LOCs). Based on these observations an inference can be made that human activity tends to congregate around these LOCs, which include roads, streams, pre-existing depressions and natural drainage areas. These areas provide paths of least resistance to mitigate the inefficiencies of moving cross-country. For this reason, these major LOCs can be used as areas to focus on when trying to detect smaller tracks and trails that tend to branch off these larger lines.

Figure 47 is the road, cart track and trail classification breakdown of correctly classified target points under canopy. Clearly, the maintenance road represents the majority of points correctly classified in Kahuku and shows the bias discussed earlier.

The modified error matrices (with correctly classified road points removed) show that tracks and trails less than or equal to 2.5 meters wide can be identified with respectable accuracies. Additionally, the chart indicates that trails less than 1.5 meters wide were identified in both Kahuku and La Selva. More importantly, the Cougar Mountain analysis confirmed that Lidar could routinely identify trails less than 1.5 meters wide.

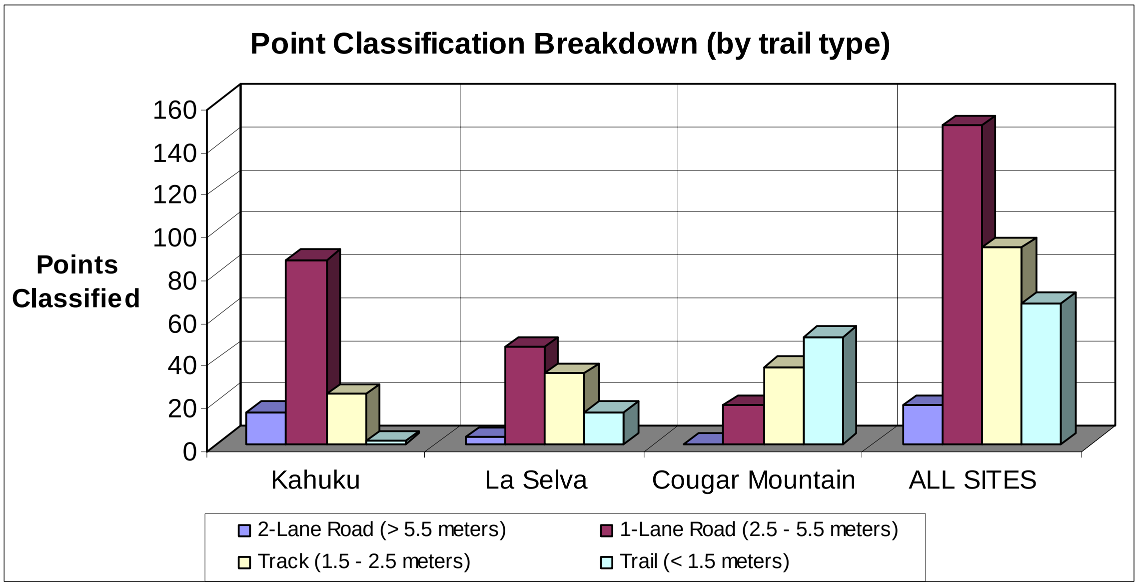


Figure 47. Classification breakdown by trail type for all points under canopy correctly identified through Lidar analysis.

The fact that the densest part of the La Selva data set was removed prior to analysis should also be restated. The overhead canopy in the remaining portion of this area was not nearly as dense as the section omitted. The trail network in the omitted section is extensive. If this entire "old growth" section had been evaluated, it is likely that very few (if any) trails would have been identified in the omitted section due to the poor quality of data available.

While Cougar Mountain best represents the ability to find smaller trails using Lidar models, it is important to reemphasize that this data was collected during leaf-off conditions. This would be expected to have an effect on the ground point density, thereby improving the ability to identify trails using surface models. There is no way to quantify this effect without performing a specific experiment for that purpose. Cougar

Mountain contains a number of trails less than 1.5 meters wide, providing an opportunity to compare and contrast differences in visual queues between correctly identified trails and missed trails found in control areas. The main difference between trails correctly identified and those missed was that the correctly identified trails had a pronounced depression wider than the traveled way. Conversely, the width of the traveled way for missed trails found in the control area also represented the extreme width (1.2 meters and 0.87 meters). Additionally, the missed trails had minimal depressions providing little or no visual indication of the trails when viewing Lidar surface models.

Finally, there are some issues to address concerning the way this experiment was conducted. The error matrices used in the statistical analysis are normally for imaging projects where every pixel is classified and verified. Obviously, with the millions of points that make up a Lidar model, it is not feasible to analyze every point. While every portion of trail found during analysis was cropped from a target area, the entire remaining area was not evaluated as a control area. This would have consumed too much time for this research project. However, it probably led to slightly inflated producer accuracies, as smaller trails not identified during the Lidar analysis may not have been identified by control points. The method used and error matrix approach was useful for this initial research and validating the feasibility of the application. However, alternative approaches should be considered for future research in this area.

Another limitation of this study falls in the area of route classification. This study evaluated single points on a trail and did not address route accessibility. Route access characteristics such as identifying the narrowest portion of the route, slope, and available turn radius were not evaluated. Nevertheless, the Lidar software tools available do provide the ability to measure these characteristics.

It should be remembered that none of the data sets analyzed in this experiment were collected with the intention of using them to identify roads and trails under canopy. The age of the technology used to collect these data sets must also be considered. As previously mentioned, even the highest PRFs used for these collects are much lower than

current systems are capable of achieving. Additionally, the analysis of the Lidar data was performed by two researchers with no prior experience or training for analyzing imagery.

Considering all these factors, the results of this thesis are very promising. The resulting accuracies represent the ability of Lidar pulses to poke through dense canopy and provide accurate surface and object models. As technology continues to improve in both Lidar sensors and post-processing software, trained intelligence analysts should be able to create highly accurate maps and descriptions of trail networks under canopy.

B. COMMON FEATURES

One common feature shared by each of the evaluated data sets, is that they all exhibited the same visual queues. In other words, the visual queues and evaluation techniques discussed in previous chapters were applicable across the board for all four data sets. From an analyst's point of view, the ability to apply a set of universal evaluation techniques, regardless of the collection platform or sensor, not only streamlines the training required to effectively evaluate Lidar data, but may also be an indication that terrain feature auto-recognition algorithms are attainable.

As mentioned earlier, if sufficient canopy poke-through (ground point density) exists, trails under canopy and those not under canopy appear the same in Lidar surface models. Based on the progression in technology and collection techniques used for each of these data sets and the PRFs of current and projected systems, it appears the poke-through capability has not reached maximum capability.

C. DIFFERENCES

The visual queues used to identify trails were generally the same for all the data sets analyzed. By visual inspection of the Lidar models as well as the accuracies calculated in the error matrices, the Kahuku data set clearly provided the best DEMs for identifying roads and trails. The Kahuku Lidar models had the least artifacts, the most accurate elevation comparisons, and the highest accuracy percentages. This can be

directly attributed to a number of differences in the sensor and collection techniques used for collecting the data. The remainder of this section will reiterate those differences and their contributions to the increased accuracies.

Perhaps the most obvious contributor is the age of the technology. The Kahuku data was collected in 2005, approximately four years after the Cougar Mountain data and eight years after the La Selva data were collected. The 70 kHz PRF is much greater than the systems used in Cougar Mountain (30 kHz), Elkhorn Slough (25 kHz), and La Selva (estimated 8 kHz) increasing the ground point density and canopy penetration capability.

The remaining differences identified as contributing to the increased foliage penetration and DEM accuracy of the Kahuku data directly relate to the collection scheme. First, the sensor was mounted on a rotary wing rather than a fixed wing aircraft. The slower aircraft speeds allows for greater dwell times over target areas. Additionally, a 360-degree flight profile around each site was utilized to simulate the step-stare technique described earlier. This creates multiple collection angles and multiple scans providing a greater probability of finding openings in the vegetation. The La Selva collection also utilized a rotary wing aircraft but flew single-pass flight lines similar to the flight patterns utilized by the fixed-wing aircraft for the other two sites (Figure 16).

D. UNANSWERED QUESTIONS

During the course of this research, the observed canopy closure varied in both vegetation type and density. It covered the full spectrum from the light closure seen in Elkhorn Slough, to some of the world's most extreme canopy closure found in La Selva. Given the age of the La Selva data analyzed in this research, the ability of current Lidar technology and techniques to penetrate the "old growth" tropical rainforests remains to be proven. Based on ground truth observations, the canopy closure observed in some portions of Kahuku where trails were accurately identified, the closure appeared to be similar in density to the canopies observed in the old growth tropical rainforest of La Selva (Figure 48). There are a few differences to note starting with tree height. In La Selva, upper canopy layers range from 44 to 55 meters high with the next layer of small, suppressed trees ranging from 10 to 25 meters. (Hofton et al., 2002) On the other hand,

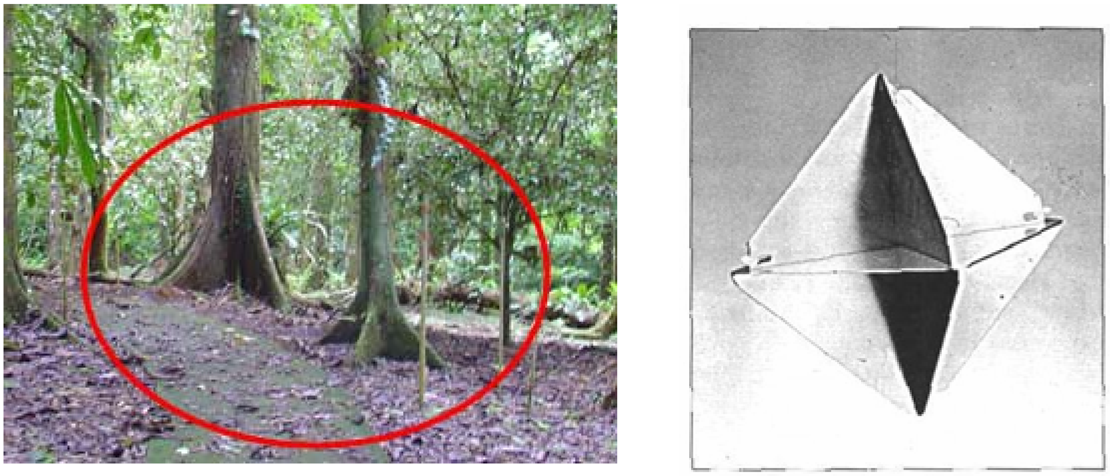
the tree heights observed in Kahuku ranged from 5 to 14 meters with no clear separation between upper canopy and the lower, suppressed understory. Another distinction is that ground cover was sparse in the old growth forest of La Selva where the canopy closure was the highest, making the surface classification processing less complex than in Kahuku. One other observation that may affect the reflection of the Lidar pulse in a jungle environment is the shape of the tree base. As seen in Figure 49, the shape resembles the radar reflector shown in Figure 49b, which may cause the base of the tree to work as a natural reflector. While the effect of this observation is unknown, it is a characteristic unique to the La Selva data set (when compared to the other three data sets). These differences are not all-inclusive, but are identified to raise the following unanswered questions:

- If the canopy closure seen in parts of Kahuku is comparable to that of "old growth" tropical rainforest, seen in La Selva, can current technology and techniques achieve similar accuracies in identifying "old growth" trails found in La Selva?
- Apart from canopy closure, what characteristics of an "old growth" tropical rainforest physically interfere with achieving adequate ground point density required to create a DEM with the sufficient detail to identify roads and trails?
- Are there different wavelengths (narrower), collection techniques (altitudes, airspeeds) or Lidar technologies (photon counting) more adequate for terrain mapping in a tropical rainforest?

(a)

(b)

Figure 48. Examples of canopy closure in (a) La Selva Biological Station, Costa Rica and (b) Kahuku Training Area, Hawaii



(a) (b)

Figure 49. Shape similarities between (a) tree base and (b) radar reflector

Much attention has been paid to the need for validation of Lidar poke-through capability in a tropical rainforest; one of the most challenging environments to capture sub-canopy topography. As stated in the introduction (Chapter I), the broadleaf evergreen biome such as that found in La Selva covers 9.7 percent of terrestrial land. (Hofton et al., 2002) The importance of the 9.7 percent cannot be overstated as it represents an environment where illicit organizations could potentially exploit.

VII. CONCLUSION

The results of the experiment conducted for this research indicate that Lidar is a viable sensor to identify roads and trails hidden under dense forest or jungle canopy. Advances in technology and collection techniques show promise for greatly increasing the ability to poke through even the densest canopies. The ability of Lidar to efficiently and cost effectively create accurate DEMs provides a distinct advantage over other survey methods that are not effective in such environments. Its day or night capability and small equipment footprint make it an ideal candidate for UAV integration mitigating manned flight risk and reducing the need for reconnaissance personnel in hostile territory.

Although this research focused exclusively on the identification of roads and trails under canopy, it is important to note that this technology has a number of other terrain analysis applications. These applications could further increase Lidar utility when performing terrain analysis during Intelligence Preparation of the Battlespace (IPB). Advanced research is currently underway to automatically recognize and extract terrain features present in Lidar models. However, this should not delay introducing this capability to the operational commander who could both benefit from and further identify operational requirements for this technology. As shown in this study, the ability of the human eye to recognize characteristics of roads or trails is very effective, even when performed by untrained terrain analysts. Imagine the results a qualified and experienced terrain analyst might achieve using the information collected by this sensor and its associated software. Other features built into current COTS software, such as line of sight evaluation, orthographic overlay capability and 3-D fly-through simulations may further enhance the terrain analysis utility of this sensor.

While conducting this research, many ideas were identified for employing this sensor to prepare the battlespace at the tactical and operational level. While the number of applications for this sensor and ongoing research and development programs within the Department of Defense continues to grow, a consolidated effort is needed to push

Lidar forward to the operational arena. The following is a list of potential research areas that would assist in product development and fielding to meet the needs of the operational commander:

- Lidar Training, Tactics and Procedure (TTP) development.
- Lidar Concept of Operations (CONOPS) for the operational commander.
- Lidar War Game to include terrain analysis, and other man-made objects under canopy.
- Incorporating Lidar into IPB process.
- Creation of Lidar Joint Mission Essential Task List (JMETL).
- Creation of Lidar Center of Excellence.

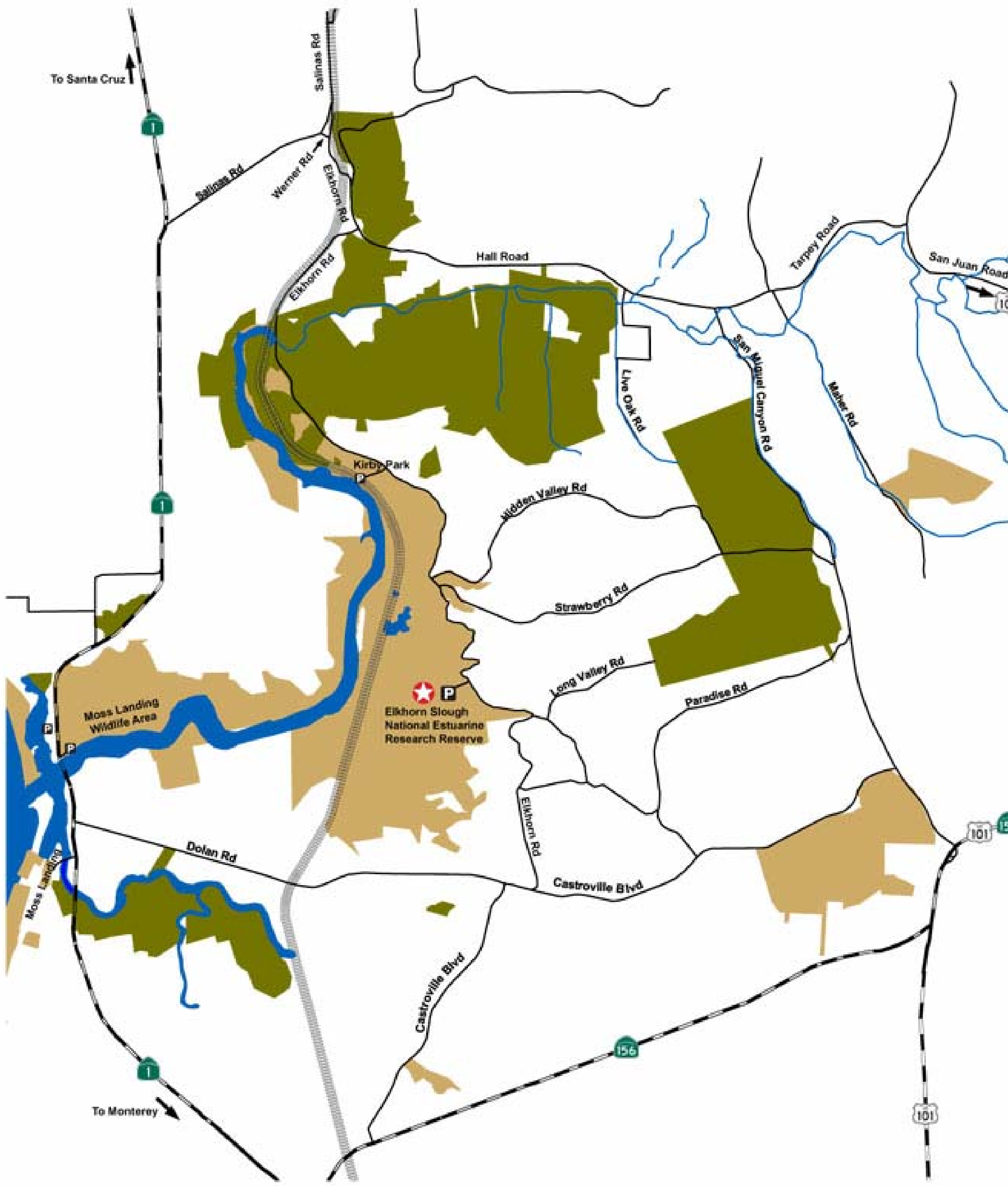
The following subjects are recommended for follow-on research for this thesis topic:

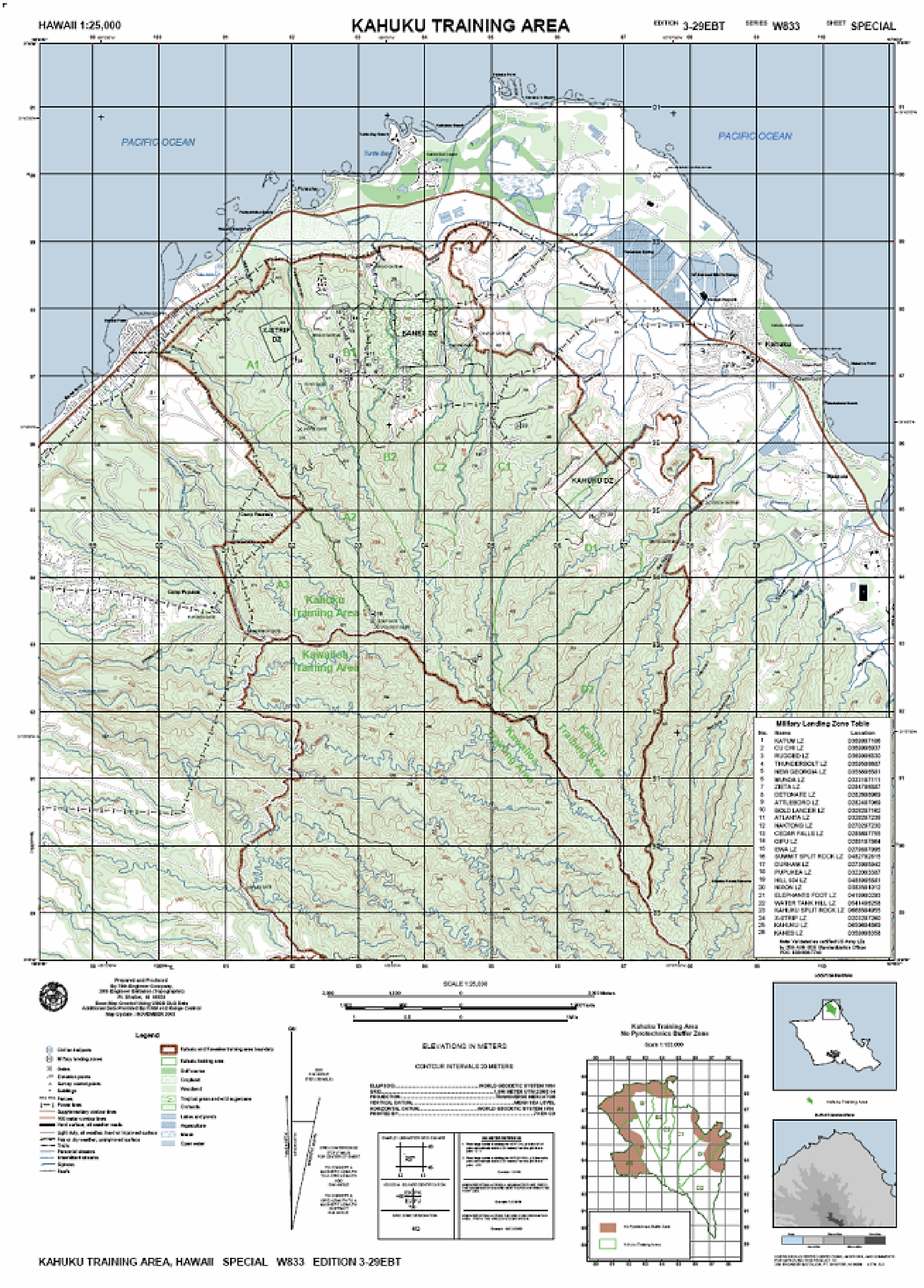
- Create auto-recognition algorithms for roads and trails.
- Conduct step-stare collection and analysis of a tropical rainforest (La Selva).
- Investigate ability to determine ground composition based on erosion patterns (drainage height profiles) as viewed in DEMs
- Evaluate digitized waveform returns to determine if intensity returns can be utilized to classify and/or auto-recognize ground composition makeup.
- Determine the effect of varying pitch angles on ground point density in different biomes.

Based on the results obtained from the four sites evaluated in this research, Lidar models can be used effectively to identify roads and trails as narrow as one meter. Additionally, the background research and experiment results from this thesis indicate the ability to effectively poke through the densest canopies and identify roads and trails may be possible in the near future. Although the unanswered question regarding the broadleaf evergreen biome remains, the ability to identify roads and trails under canopies that nearly rival that of La Selva, provides a capability previously unattainable with other remote sensors.

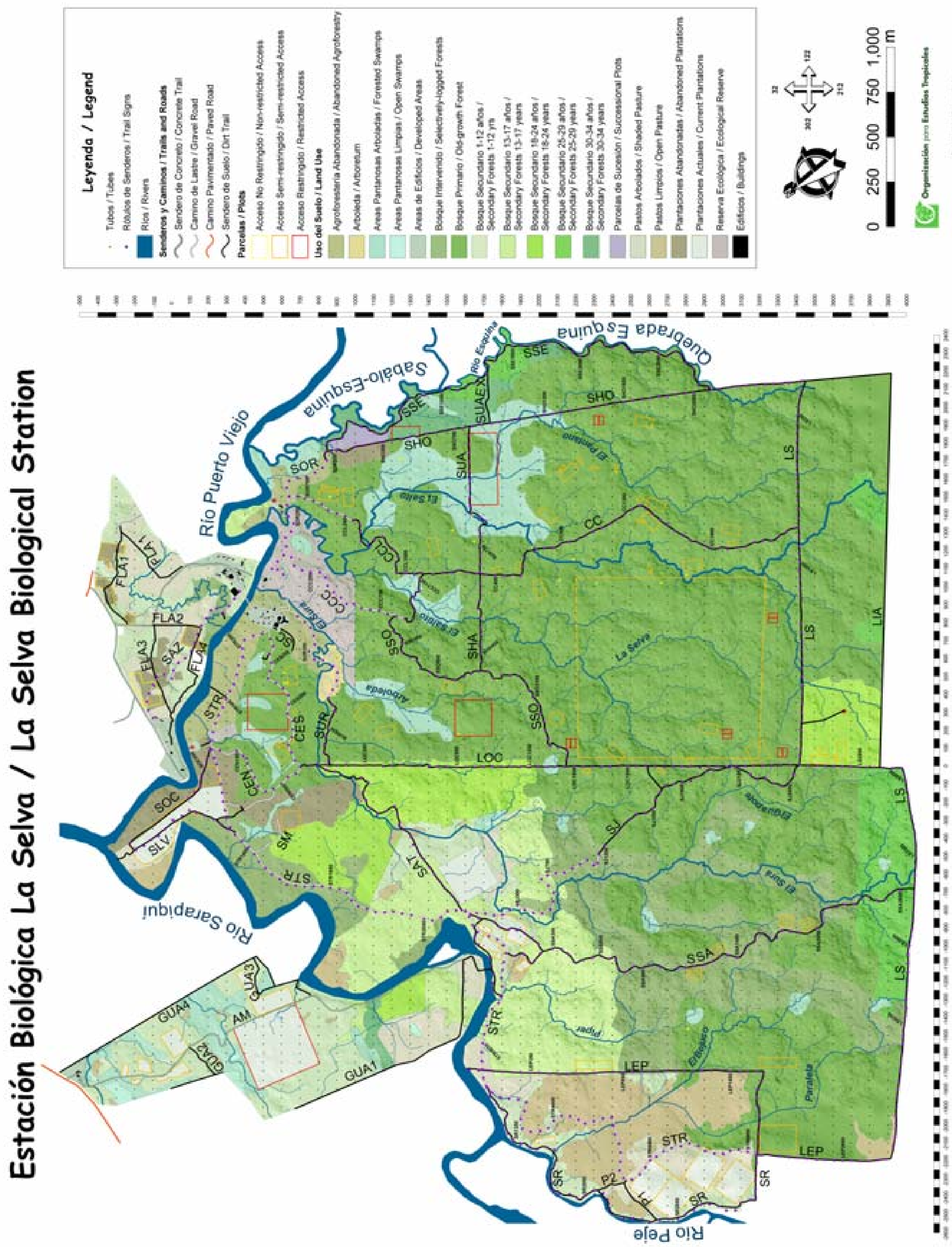
APPENDIX A – TEST AREA MAPS

Elkhorn Slough Map
(From: http://www.elkhornslough.org/map.htm)

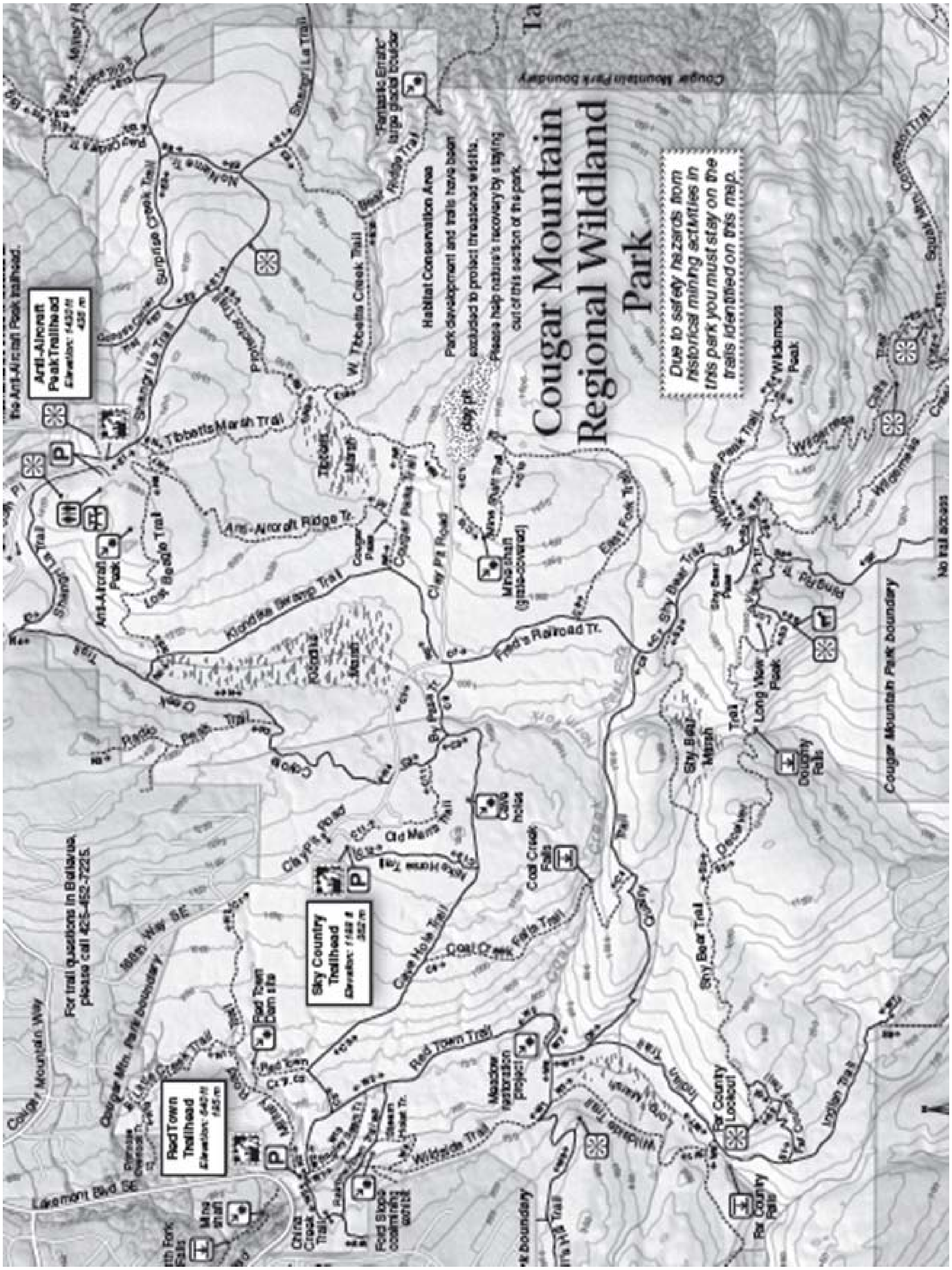




HAWAII 1:25,000
KAHUKU TRAINING AREA
EDITION 3-29EBT
SERIES W833
SHEET SPECIAL
PACIFIC OCEAN
PACIFIC OCEAN
X-STRIP DZ
KANES DZ
KAHUKU DZ
A1
A2
A3
B1
B2
C1
C2
D1
D2
Kahuku
Camp Pupukea
Kahuku Training Area
Kawailoa Training Area
Kawailoa Training Area
Kahuku Training Area
Military Landing Zone Table
No. Name Location
1 KATUM LZ
2 CU CHI LZ
3 RUGGED LZ
4 THUNDERBOLT LZ
5 NEW GEORGIA LZ
6 MUNDA LZ
7 ZETA LZ
8 DETONATE LZ
9 ATTLEBORO LZ
10 BOLD LANCER LZ
11 ATLANTA LZ
12 NAKTONG LZ
13 CEDAR FALLS LZ
14 GIFU LZ
15 EWA LZ
16 SUMMIT SPLIT ROCK LZ
17 DURHAM LZ
18 PUPUKEA LZ
19 HILL 604 LZ
20 NIXON LZ
21 ELEPHANTS FOOT LZ
22 WATER TANK HILL LZ
23 KAHUKU SPLIT ROCK LZ
24 X-STRIP LZ
25 KAHUKU LZ
26 KANES LZ
SCALE 1:25,000
Legend
ELEVATIONS IN METERS
CONTOUR INTERVALS 20 METERS
Kahuku Training Area
No Pyrotechnics Buffer Zone
KAHUKU TRAINING AREA, HAWAII SPECIAL W833 EDITION 3-29EBT



Estación Biológica La Selva / La Selva Biological Station
Leyenda / Legend
Tubos / Tubes
Rótulos de Senderos / Trail Signs
Ríos / Rivers
Senderos y Caminos / Trails and Roads
Sendero de Concreto / Concrete Trail
Camino de Lastre / Gravel Road
Camino Pavimentado / Paved Road
Sendero de Suelo / Dirt Trail
Parcelas / Plots
Acceso No Restringido / Non-restricted Access
Acceso Semi-restringido / Semi-restricted Access
Acceso Restringido / Restricted Access
Uso del Suelo / Land Use
Agroforestería Abandonada / Abandoned Agroforestry
Arboleda / Arboretum
Areas Pantanosas Arboladas / Forested Swamps
Areas Pantanosas Limpias / Open Swamps
Areas de Edificios / Developed Areas
Bosque Intervenido / Selectively-logged Forests
Bosque Primario / Old-growth Forest
Bosque Secundario 1-12 años / Secondary Forests 1-12 yrs
Bosque Secundario 13-17 años / Secondary Forests 13-17 years
Bosque Secundario 18-24 años / Secondary Forests 18-24 years
Bosque Secundario 25-29 años / Secondary Forests 25-29 years
Bosque Secundario 30-34 años / Secondary Forests 30-34 years
Parcelas de Sucesión / Successional Plots
Pastos Arbolados / Shaded Pasture
Pastos Limpios / Open Pasture
Plantaciones Abandonadas / Abandoned Plantations
Plantaciones Actuales / Current Plantations
Reserva Ecológica / Ecological Reserve
Edificios / Buildings
0 250 500 750 1,000 m
Organización para Estudios Tropicales
Río Puerto Viejo
Río Sarapiquí
Río Peje
Sabalo-Esquina
Quebrada Esquina



Cougar Mountain Regional Wildland Park
Due to safety hazards from historical mining activities in this park you must stay on the trails identified on this map.
Habitat Conservation Area
Anti-Aircraft Peak Trailhead
Sky Country Trailhead
Red Town Trailhead
Cougar Mountain Park boundary
Klondike Swamp Trail
Fred's Railroad Tr.
Anti-Aircraft Ridge Tr.
Tibbetts Marsh Trail
W. Tibbetts Creek Trail
Shy Bear Trail
Wildside Trail
Red Town Trail
Coal Creek Falls Trail

APPENDIX B – ERROR MATRICES

KAHUKU ERROR MATRICES

SITE 1				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	7	0	7	100%
No Trail	0	5	5	100%
Column Total	7	5	12	
Producer Accuracy	100%	100%		
		Overall Accuracy	100%	

SITE 2				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	18	0	18	100%
No Trail	0	13	13	100%
Column Total	18	13	31	
Producer Accuracy	100%	100%		
		Overall Accuracy	100%	

SITE 3				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	13	0	13	100%
No Trail	0	10	10	100%
Column Total	13	10	23	
Producer Accuracy	100%	100%		
		Overall Accuracy	100%	

SITE 4				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	20	0	20	100%
No Trail	7	11	18	61%
Column Total	27	11	38	
Producer Accuracy	74%	100%		
		Overall Accuracy	82%	

SITE 5				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	10	0	10	100%
No Trail	1	8	9	89%
Column Total	11	8	19	
Producer Accuracy	91%	100%		
		Overall Accuracy	95%	

SITE 6				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	81	8	89	91%
No Trail	3	46	49	94%
Column Total	84	54	138	
Producer Accuracy	96%	85%		
		Overall Accuracy	92%	

TOTALS FOR ALL POINTS				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	149	8	157	95%
No Trail	11	93	104	89%
Column Total	160	101	261	
Producer Accuracy	93%	92%		
		Overall Accuracy	93%	

TOTALS FOR COVERED POINTS				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	100	8	108	93%
No Trail	10	79	89	89%
Column Total	110	87	197	
Producer Accuracy	91%	91%		
		Overall Accuracy	91%	

LA SELVA ERROR MATRICES

LA SELVA SITE (All Points)				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**101**	31	132	77%
No Trail	5	**101**	106	95%
Column Total	106	132	238	
Producer Accuracy	95%	77%		
	Overall Accuracy		**85%**	

LA SELVA SITE (Covered Points)				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**61**	20	81	75%
No Trail	5	**58**	63	92%
Column Total	66	78	144	
Producer Accuracy	92%	74%		
	Overall Accuracy		**83%**	

ALIEN HEAD SITE (All Points)				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**28**	25	53	53%
No Trail	1	**51**	52	98%
Column Total	29	76	105	
Producer Accuracy	97%	67%		
	Overall Accuracy		**75%**	

ALIEN HEAD SITE (Covered Points)				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**23**	21	44	52%
No Trail	1	**41**	42	98%
Column Total	24	62	86	
Producer Accuracy	96%	66%		
	Overall Accuracy		**74%**	

TOTALS FOR ALL POINTS				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**129**	56	185	70%
No Trail	6	**152**	158	96%
Column Total	135	208	343	
Producer Accuracy	96%	73%		
	Overall Accuracy		**82%**	

TOTALS FOR COVERED POINTS				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**84**	41	125	67%
No Trail	6	**99**	105	94%
Column Total	90	140	230	
Producer Accuracy	93%	71%		
	Overall Accuracy		**80%**	

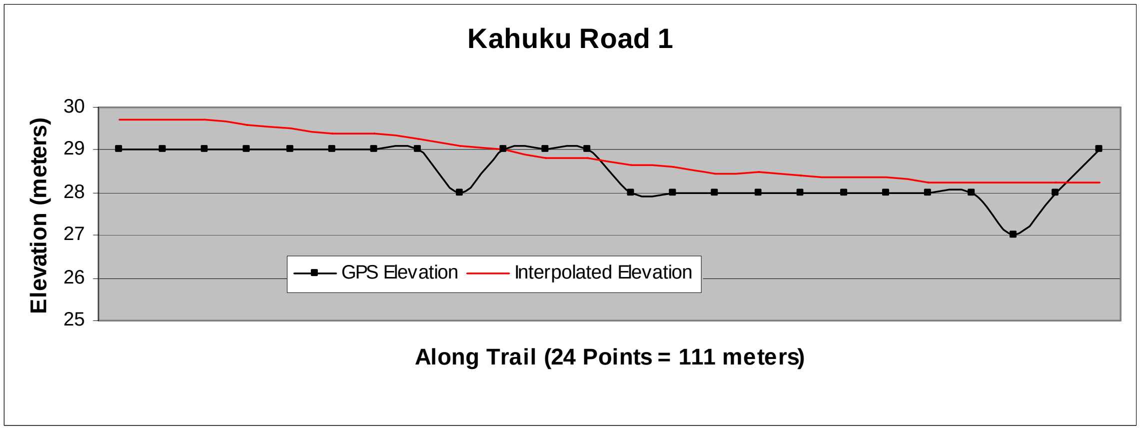
COUGAR MOUNTAIN ERROR MATRICES

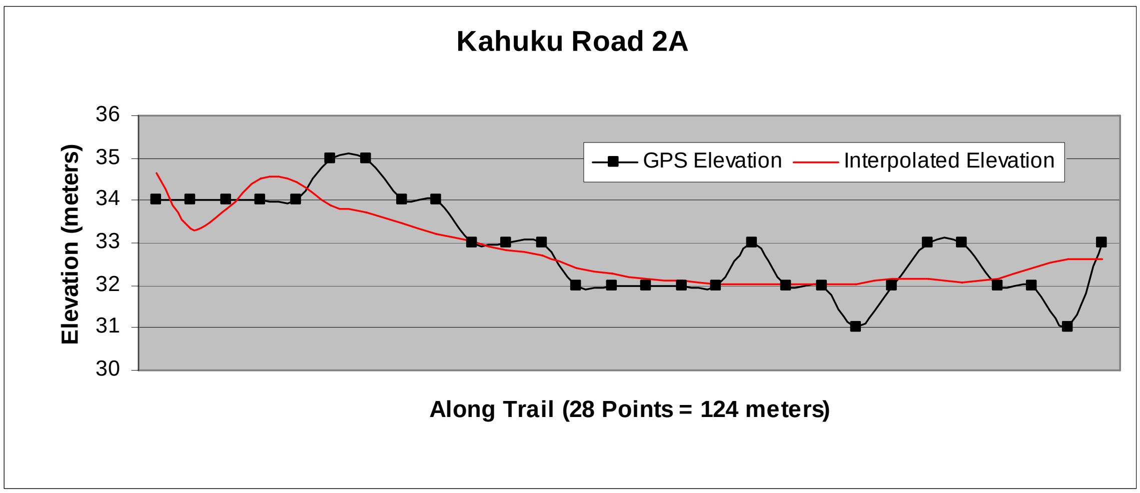
COUGAR MOUNTAIN (ALL POINTS)				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**110**	51	161	68%
No Trail	11	**90**	101	89%
Column Total	121	141	262	
Producer Accuracy	91%	64%		
	Overall Accuracy		**76%**	

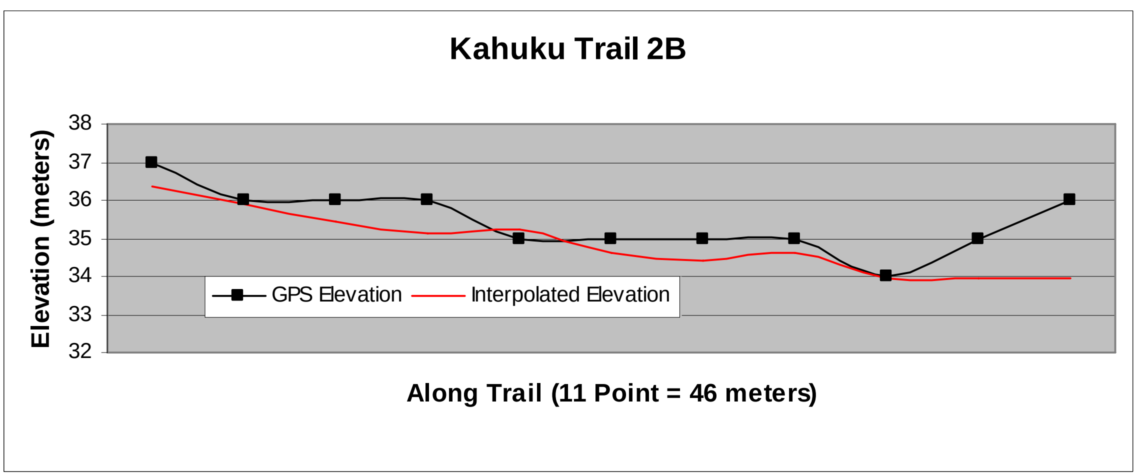
COUGAR MOUNTAIN (COVERED POINTS)				
	Reference Data			
Classification Data	Trail	No Trail	Row Total	User Accuracy
Trail	**104**	51	155	67%
No Trail	11	**90**	101	89%
Column Total	115	141	256	
Producer Accuracy	90%	64%		
	Overall Accuracy		**76%**	

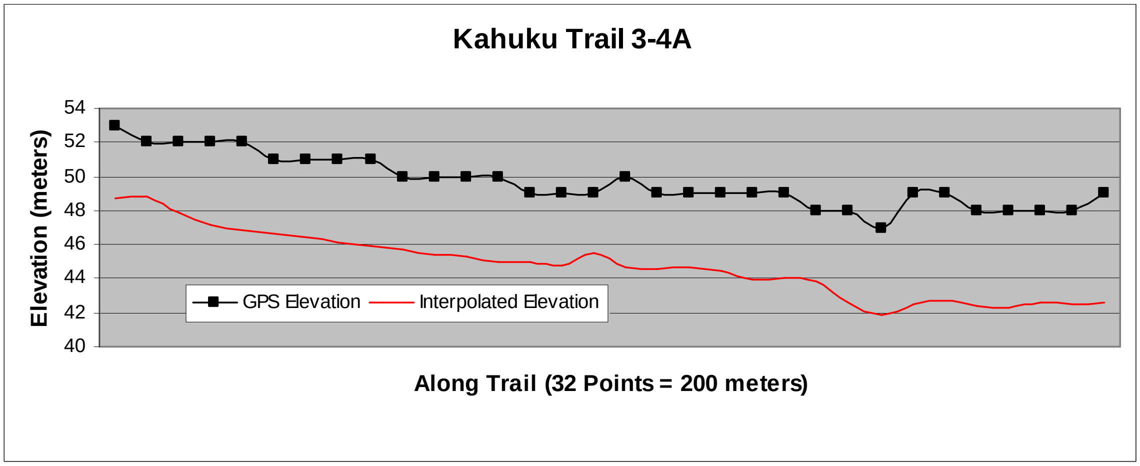
APPENDIX C – LIDAR AND GPS ELEVATION COMPARISONS

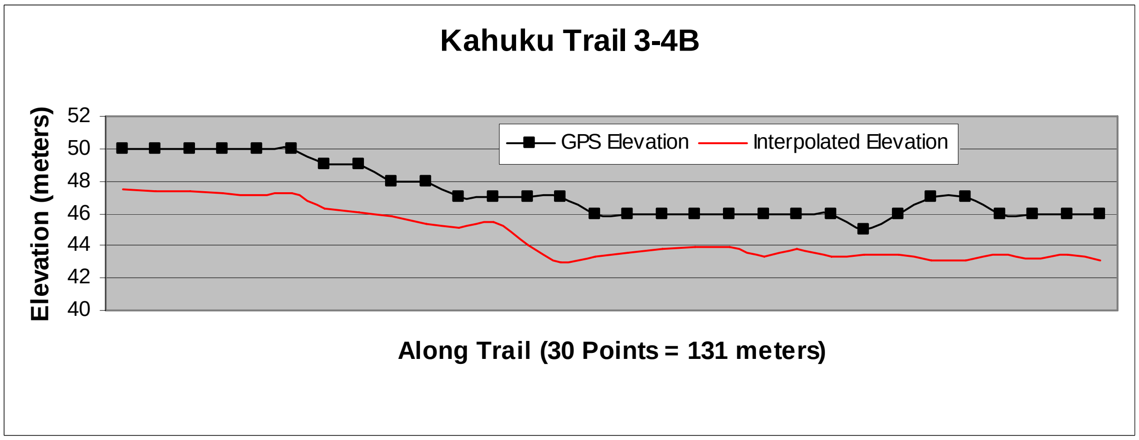
KAHUKU TRAIL ELEVATION COMPARISON CHARTS

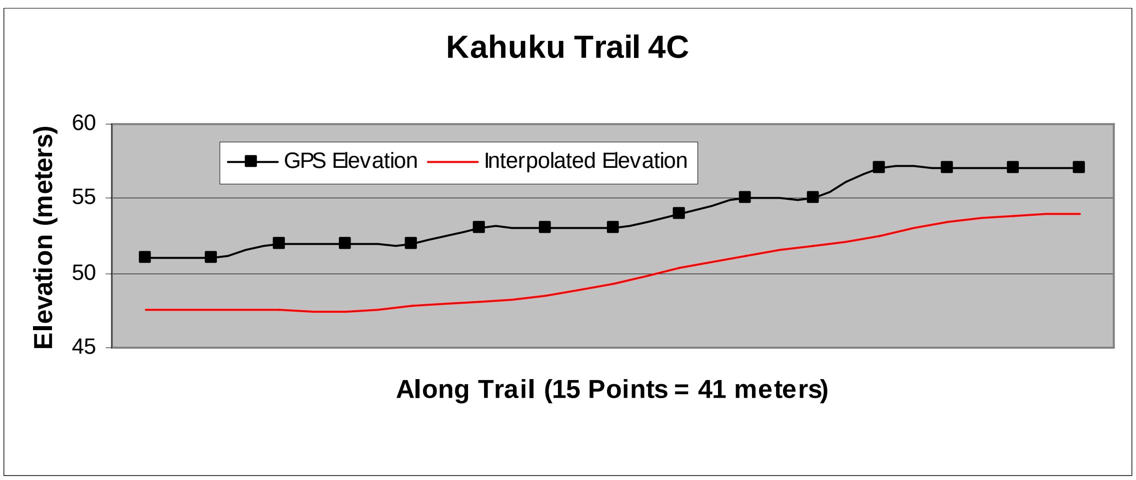


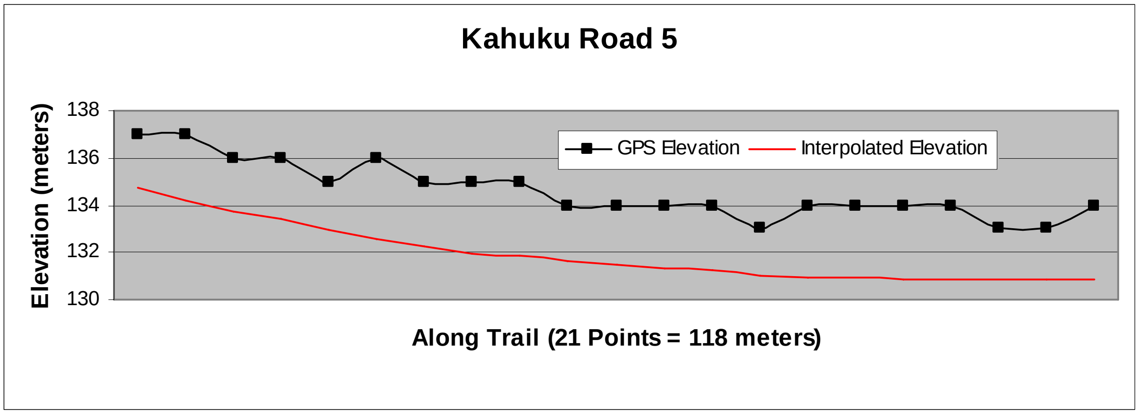


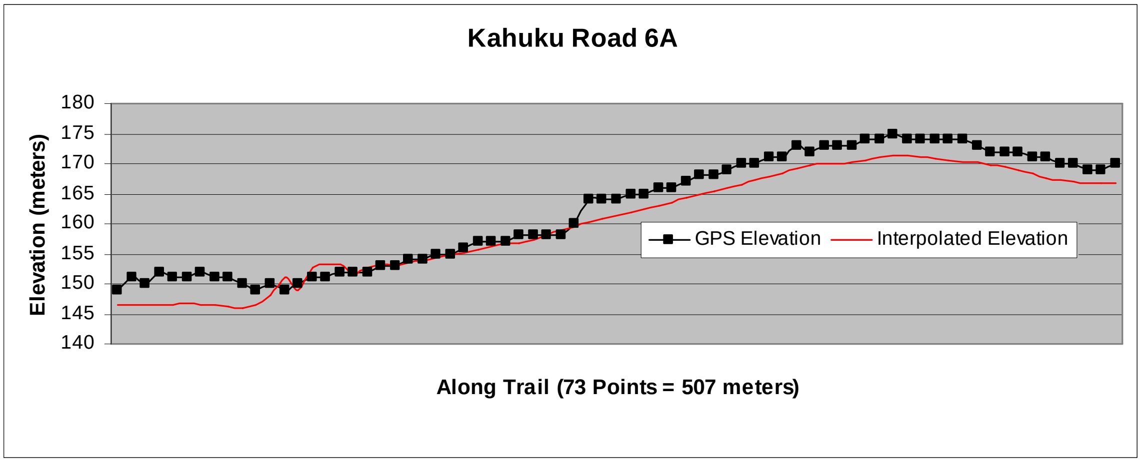


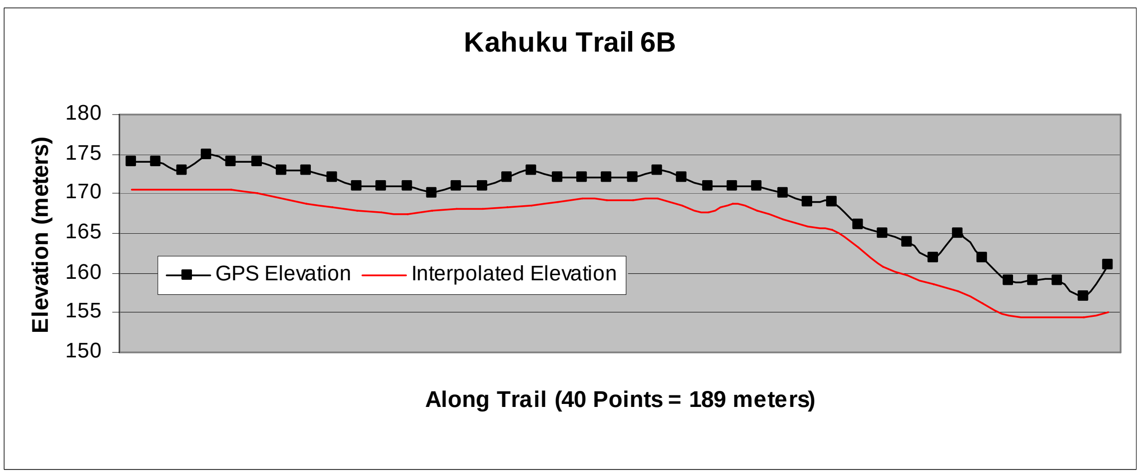

Kahuku Trail 3-4A
Elevation (meters)
54
52
50
48
46
44
42
40
GPS Elevation
Interpolated Elevation
Along Trail (32 Points = 200 meters)

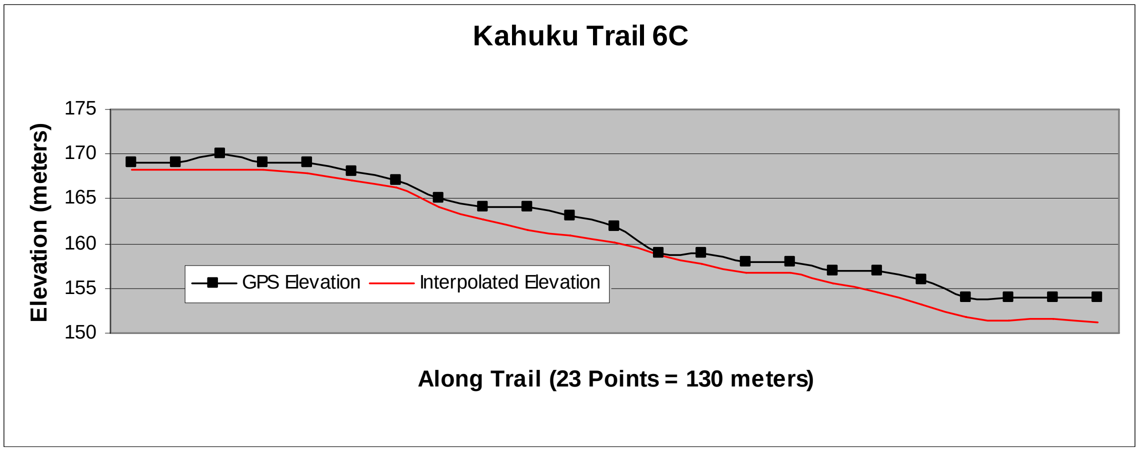

Kahuku Trail 3-4B
Elevation (meters)
52
50
48
46
44
42
40
GPS Elevation
Interpolated Elevation
Along Trail (30 Points = 131 meters)

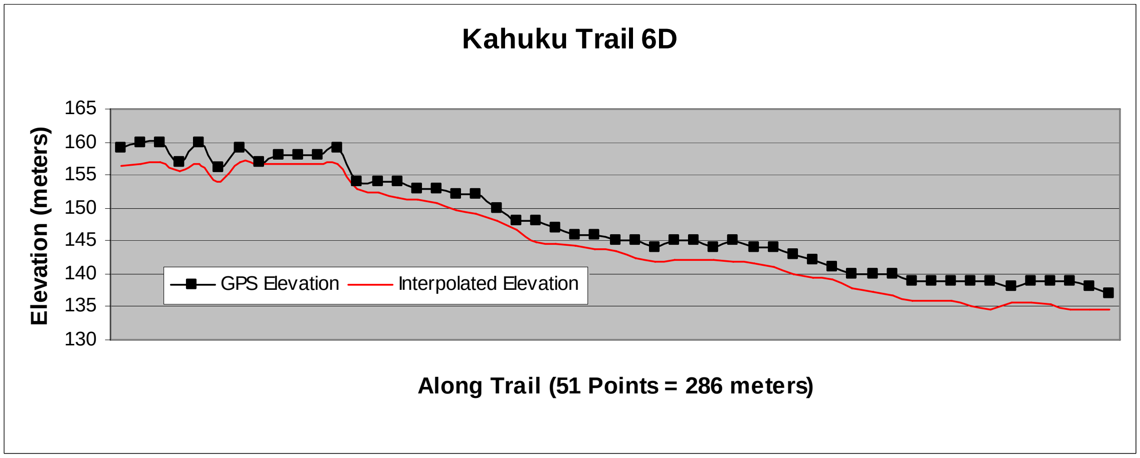

Kahuku Trail 4C
Elevation (meters)
60
55
50
45
GPS Elevation
Interpolated Elevation
Along Trail (15 Points = 41 meters)

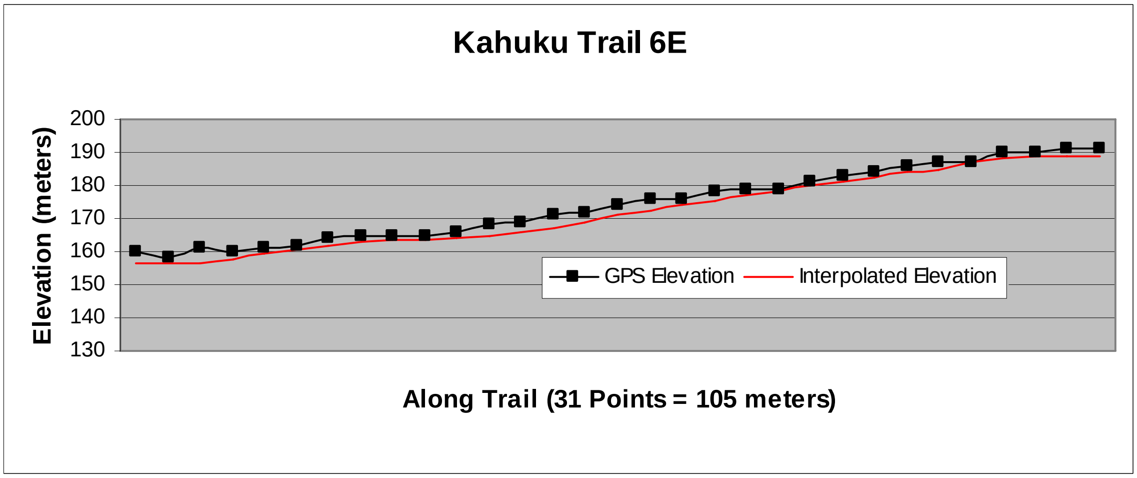

Kahuku Road 5
Elevation (meters)
138
136
134
132
130
GPS Elevation
Interpolated Elevation
Along Trail (21 Points = 118 meters)

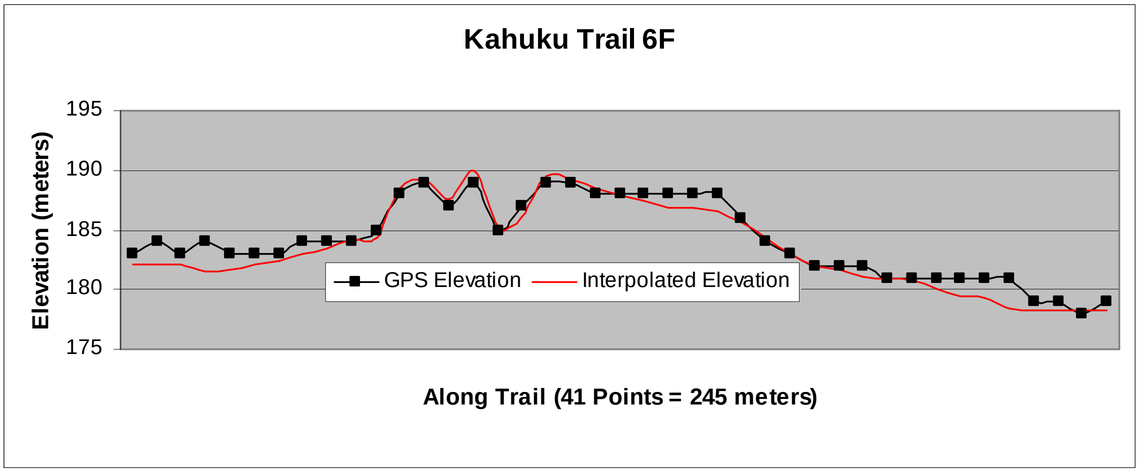

Kahuku Road 6A
Elevation (meters)
180
175
170
165
160
155
150
145
140
GPS Elevation
Interpolated Elevation
Along Trail (73 Points = 507 meters)

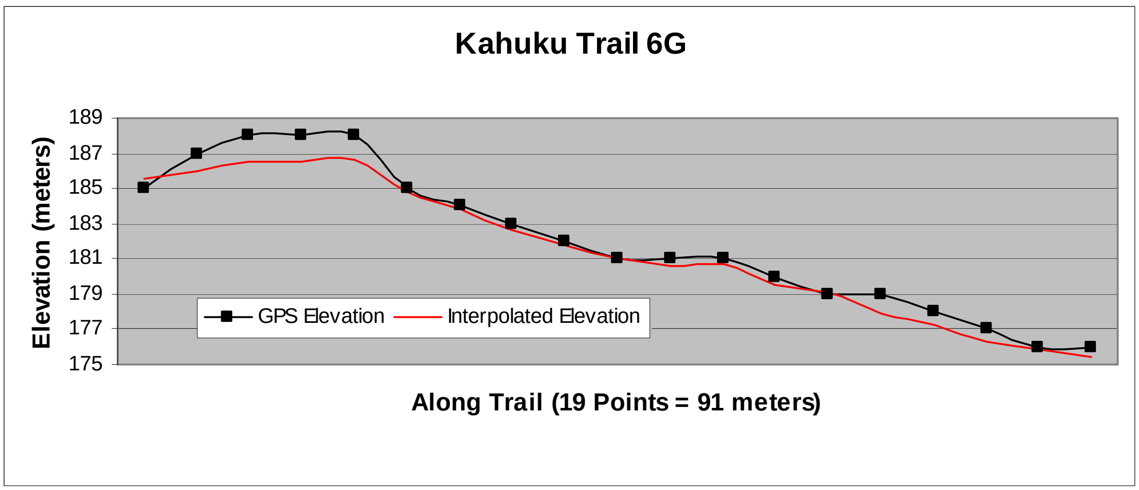

Kahuku Trail 6B
Elevation (meters)
180
175
170
165
160
155
150
GPS Elevation
Interpolated Elevation
Along Trail (40 Points = 189 meters)

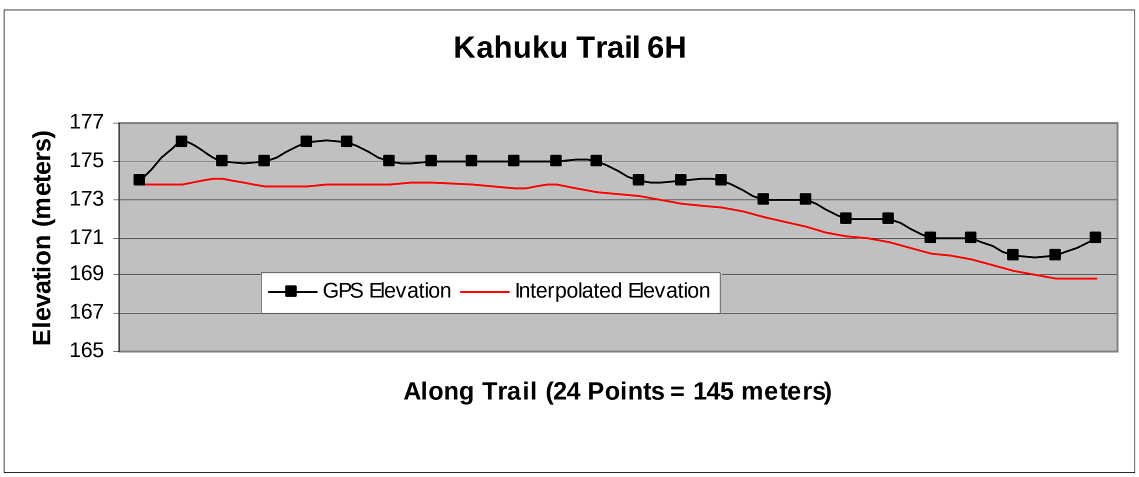

Kahuku Trail 6C
Elevation (meters)
175
170
165
160
155
150
GPS Elevation
Interpolated Elevation
Along Trail (23 Points = 130 meters)


Kahuku Trail 6D
Elevation (meters)
165
160
155
150
145
140
135
130
GPS Elevation
Interpolated Elevation
Along Trail (51 Points = 286 meters)

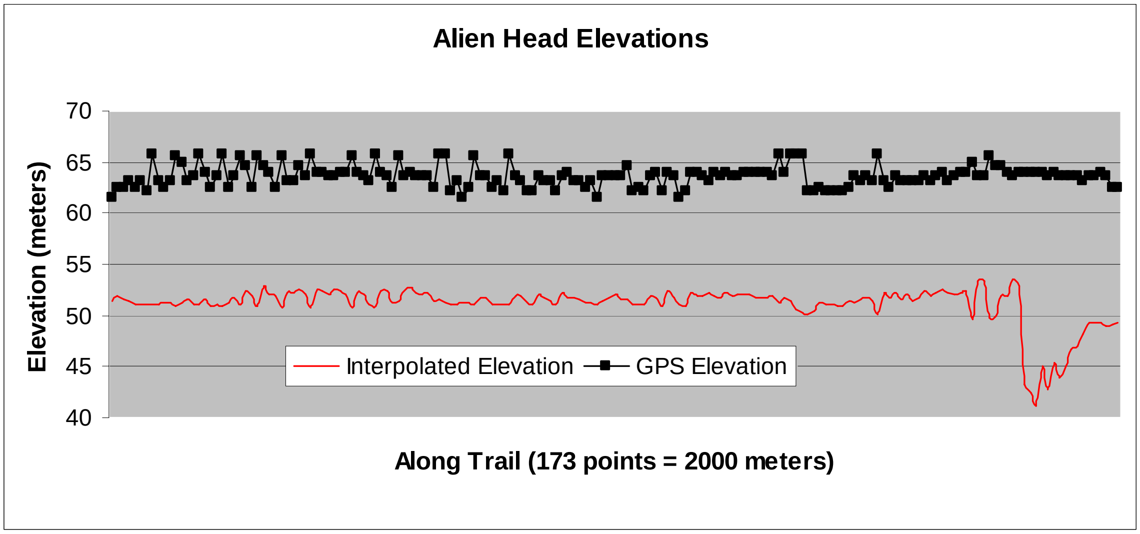

Kahuku Trail 6E
Elevation (meters)
200
190
180
170
160
150
140
130
GPS Elevation
Interpolated Elevation
Along Trail (31 Points = 105 meters)


Kahuku Trail 6F
Elevation (meters)
195
190
185
180
175
GPS Elevation
Interpolated Elevation
Along Trail (41 Points = 245 meters)

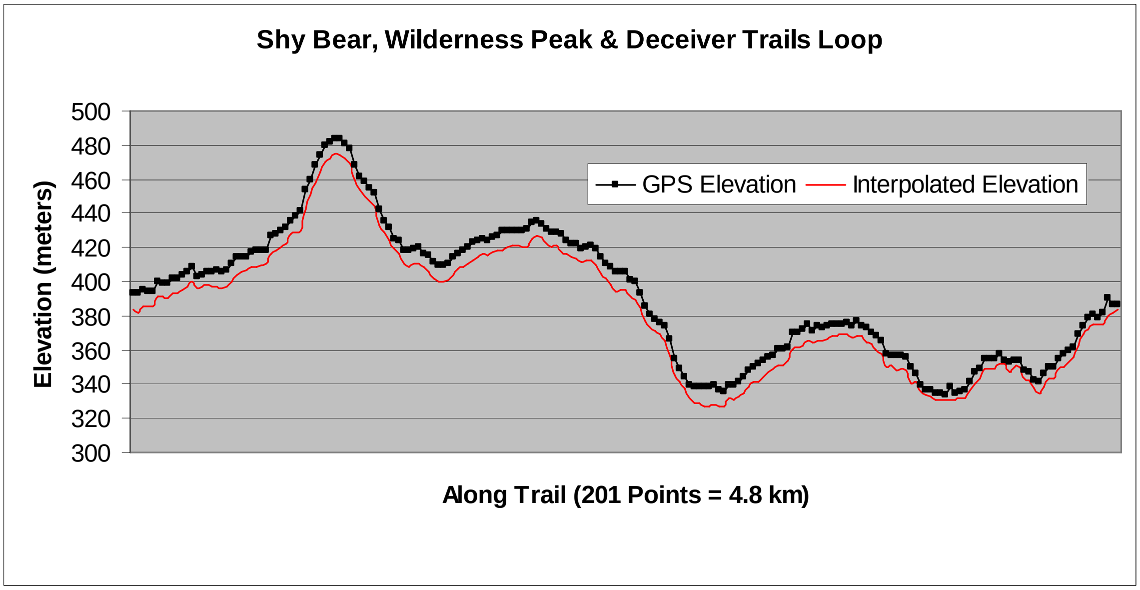

Kahuku Trail 6G
Elevation (meters)
189
187
185
183
181
179
177
175
GPS Elevation
Interpolated Elevation
Along Trail (19 Points = 91 meters)

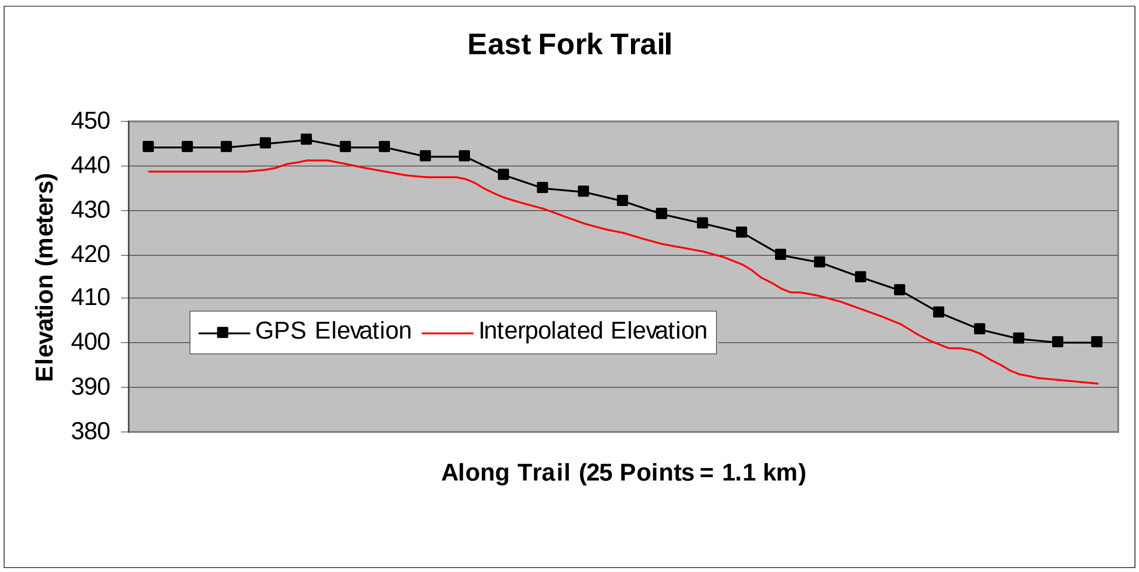

Kahuku Trail 6H
Elevation (meters)
177
175
173
171
169
167
165
GPS Elevation
Interpolated Elevation
Along Trail (24 Points = 145 meters)

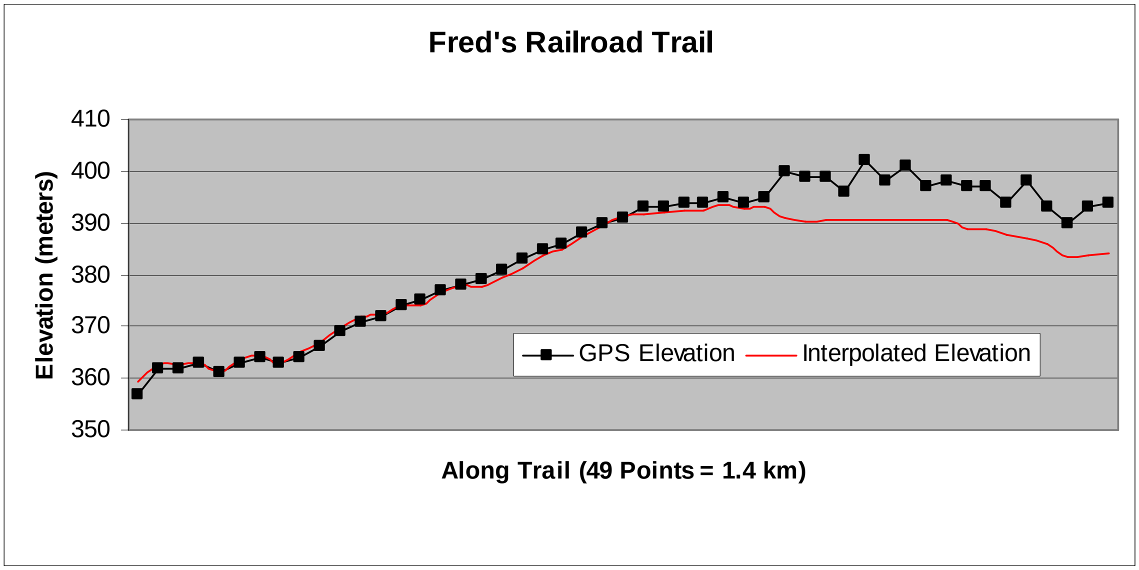
ALIEN HEAD (LA SELVA) TRAIL ELEVATION COMPARISON CHART

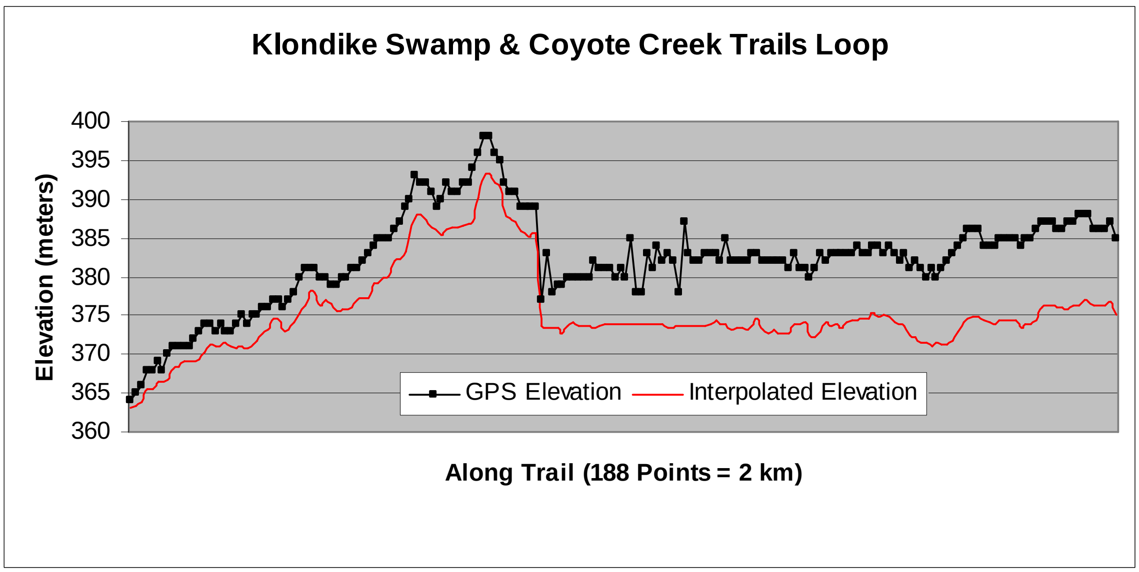


COUGAR MOUNTAIN TRAIL ELEVATION COMPARISON CHARTS






Fred's Railroad Trail
410
400
390
380
370
360
350
Elevation (meters)
GPS Elevation
Interpolated Elevation
Along Trail (49 Points = 1.4 km)

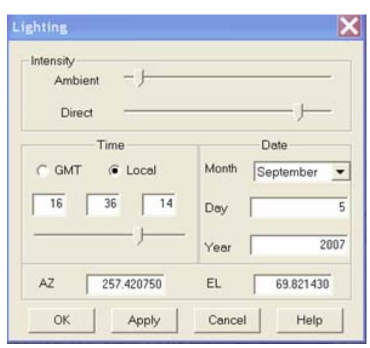

Klondike Swamp & Coyote Creek Trails Loop
400
395
390
385
380
375
370
365
360
Elevation (meters)
GPS Elevation
Interpolated Elevation
Along Trail (188 Points = 2 km)

APPENDIX D – TRAIL IDENTIFICATION PROCESS

A number of useful functions within Quick Terrain Modeler and a process (flow provided in Appendix E) for identifying possible roads and trails were identified throughout the data analysis. Initially, the bare earth extraction plug-in must be applied to the data set. At this time, the plug-in requires data to be in the XYZ file format. If the data is not initially in this format, in some cases it is possible to import the files into Quick Terrain Modeler and then "re-save" them in the XYZ format. The Elkhorn Slough data was initially in the LAS file format.

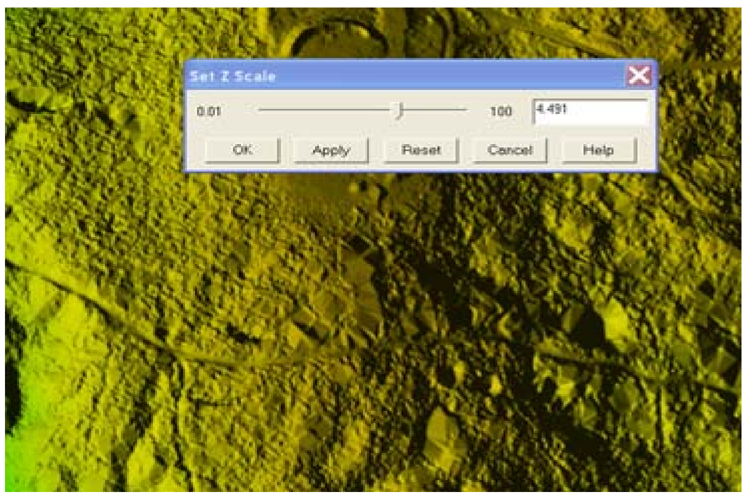
Once the bare earth plug-in is applied, the surface model needs to be imported. Upon being imported, the surface model may appear to be "distorted." Clicking on the *Toggle Vertex Colors* button may fix the issue. At any time while viewing a data set, the "image" may be zoomed in or out, turned and tilted to view from a number of different angles.

The *Set Lighting* button is one of the most important tools to utilize when visualizing the data. Three types of lighting can be manipulated to make identifying trails easier. There is a "slide" used to change each type of lighting. Ambient is the first lighting normally changed. Normally, sliding the ambient lighting to the darker side makes the surface features stand out better. The direct lighting slide was found to be less useful. It was normally left on the lighter end of the spectrum and rarely manipulated. The time bar is extremely useful in varying the views of the data.



The best views were consistently when the local time bar was set near 0700 or 1800. This is a personal preference and will be selected by the analyst through experimentation with the data. It may be useful to go back and readjust the lighting throughout the data analysis in order to provide different views. After adjusting the lighting, this will provide the initial view for identifying possible roads and trails. In this view, they will appear as depressions in the surface or "straight" lines suggesting their presence. With this view, creeks and other drainage areas may have similar appearances to roads and trails.

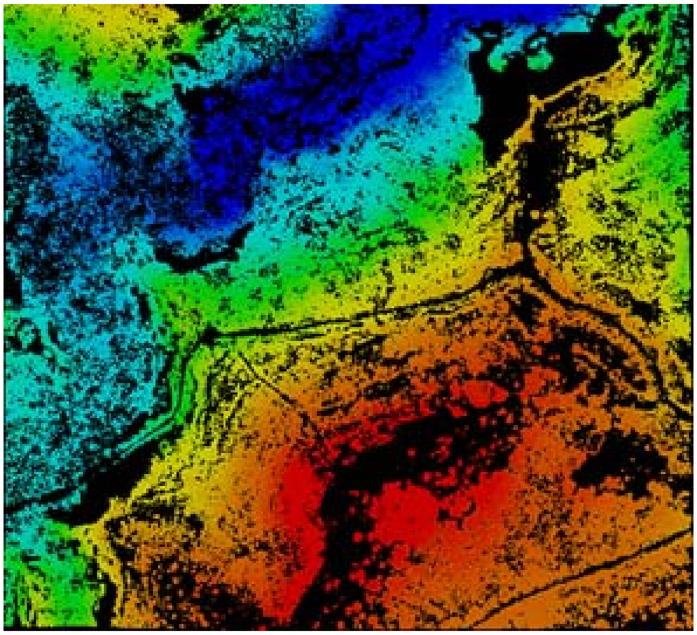
While still dealing with the surface model, another very useful tool in Quick Terrain Modeler is the *Rescale Model Heights* button. This allows the analyst to exaggerate the height differences within the model.



It is extremely useful for the verification or confirmation of smaller trails that do not have a large depression.

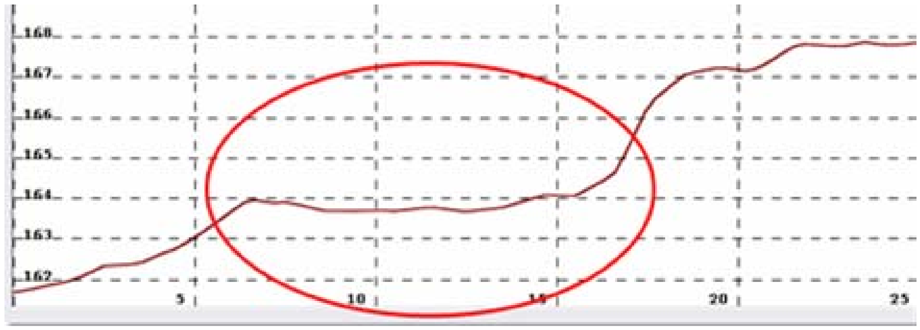
Next, the object file can be imported on top of the surface file. With both files open, it is easy to switch between showing either file individually and overlaying the two files using the *Show/Hide Models* button. The object file can be effectively utilized to help verify trails previously identified using the surface model or identify other possible trails not visible using the surface file. By switching the view back and forth between overlaying the object file on top of the surface file and viewing the object file individually, obstructions preventing passage over or through an area previously

identified as a road or trail can be identified. Roads, trails and bare earth areas (minimal or no vegetation) should appear as black areas (no data points present) when viewing an object file independently.



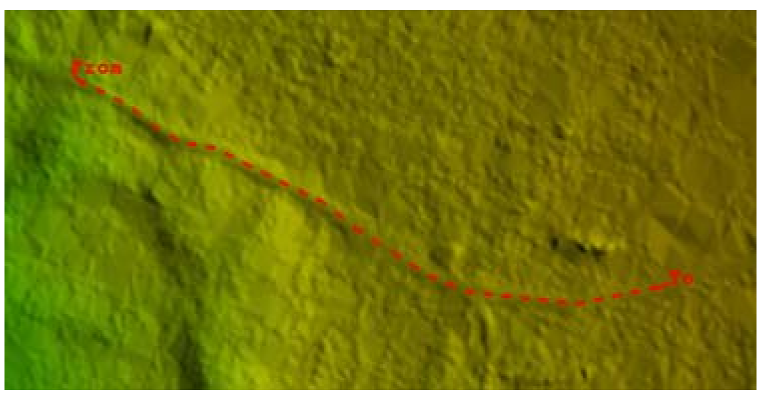
Again, look for straight lines indicating the presence of a road or trail. In most cases, these are expected to line up directly with those roads and trails identified using the surface model. In addition, this method should be useful for identifying trails cut out of vegetation but having little or no depression to distinguish them from the surrounding area.

It will likely be useful to categorize roads or trails after they have been located and identified as such. The tool found to be most useful in this regard is the *Place Mensuration Line* button. A number of trail characteristics can be determined by using this tool. First, by placing a line "across" a road or trail, the width of the road/trail can be determined at a given point. In addition, by using the *Examine Height Profile* button under the Mensuration Data, the trail depression can be determined.

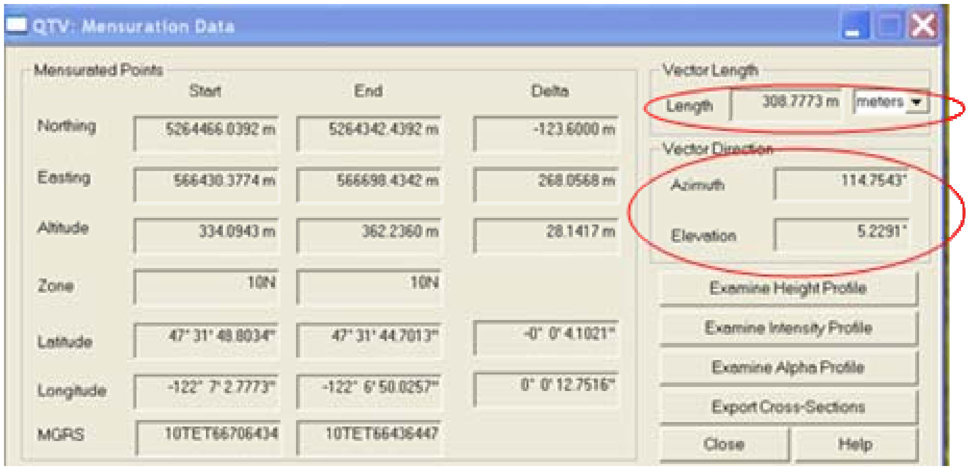


This tool also provides information regarding the slope of the surrounding area. For example, is the road/trail the low point of the area or is it on the side of a hill where it slopes up on one side and down on the other. Additionally, by using this tool with the surface, object and cloud files open, some characteristics of the surround vegetation at any given point can also be determined.

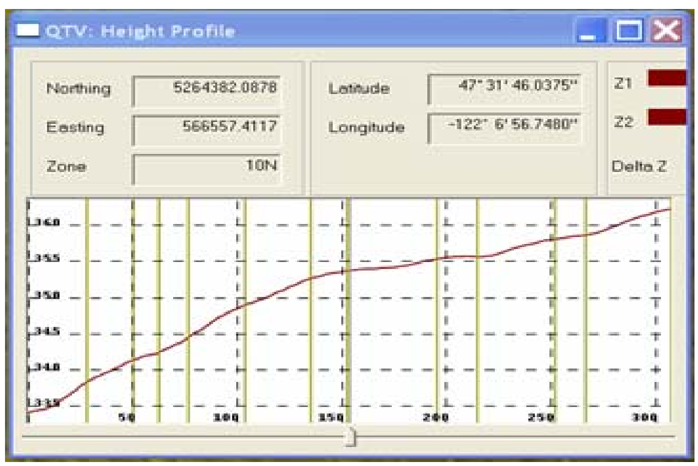
Similarly, using the same function and placing a mensuration line down the middle of a road/trail can provide additional characteristics useful for planning purposes.



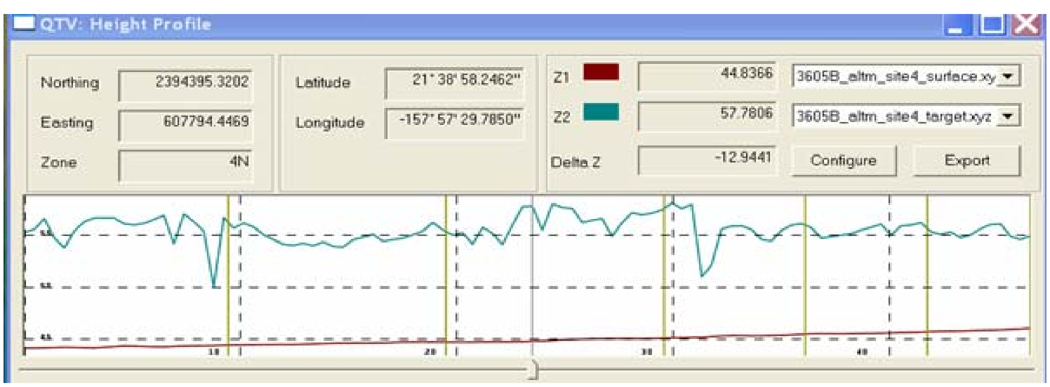
The "Vector Length" box provides the actual length of the entire line drawn from start to finish (the line can be drawn in a number of segments and does not have to be straight). The "Vector Direction" box gives the direction (in degrees) from the starting point to the ending point of the line. It also contains the slope of a vector going directly from the starting point to the ending point of the line.



Again, utilizing the *Examine Height Profile* button can provide additional useful information. It gives a visual (graph format) of the slope of the trail.



When used with the surface, object and cloud files open, it provides the canopy height of vegetation over a particular road/trail.



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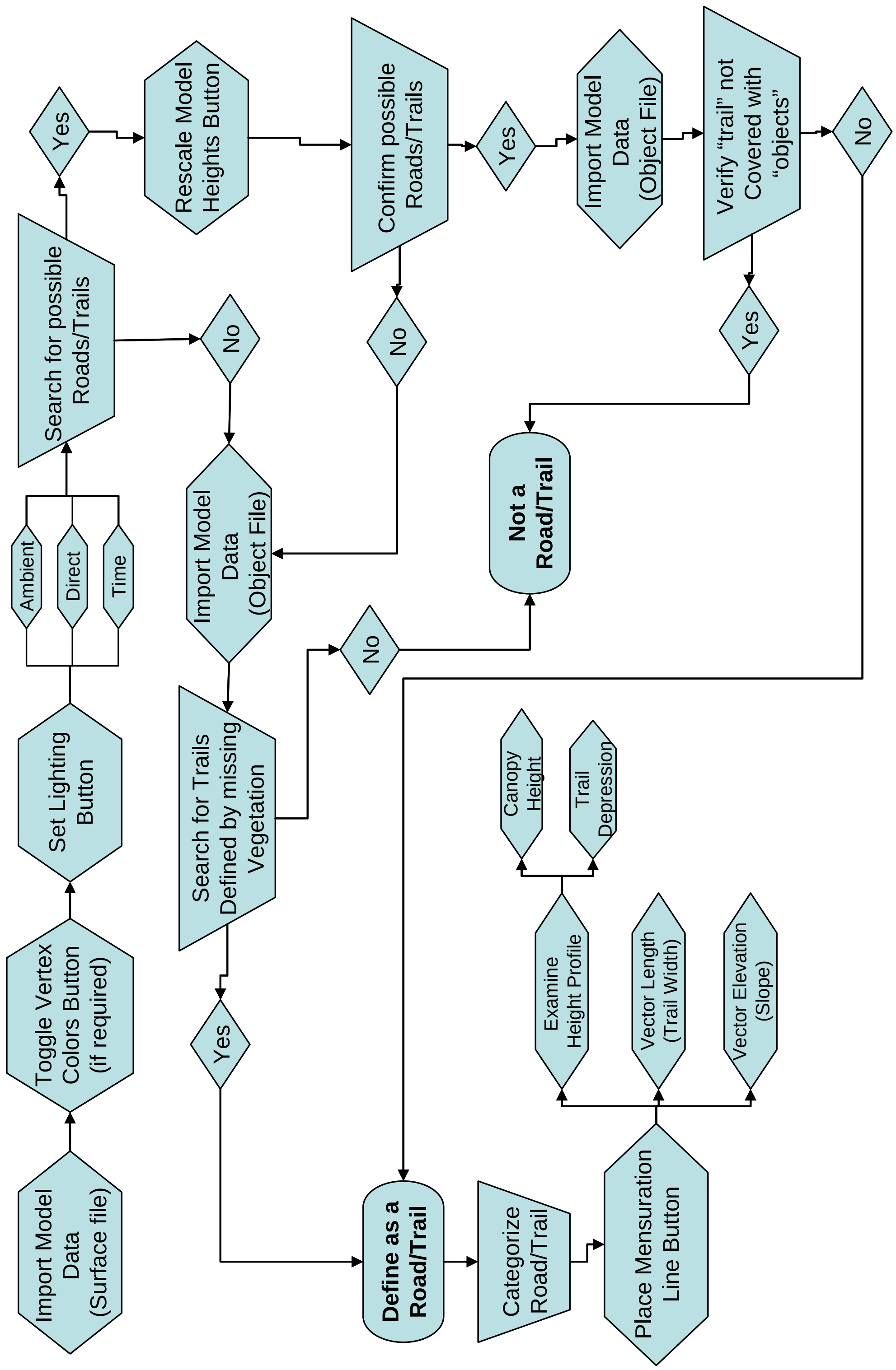
APPENDIX E – TRAIL IDENTIFICATION FLOW CHART



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APPENDIX F – EXAMPLES OF GROUND TRUTH

KAHUKU

Traveled way 2.5 meters wide (Site 3)

Traveled way 4.5 meters wide (Site 3)

Traveled Way 3.5 meters wide (Site 4)

LA SELVA / ALIEN HEAD


Traveled way 0.6 meters wide (La Selva)


Traveled way 2.5 meters wide (La Selva)


Traveled way 0.7 meters wide (Alien Head)

COUGAR MOUNTAIN


Traveled way 0.9 meters wide


Traveled way 1.14 meters wide


Traveled way 1.44 meters wide

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